

AD-A168 784

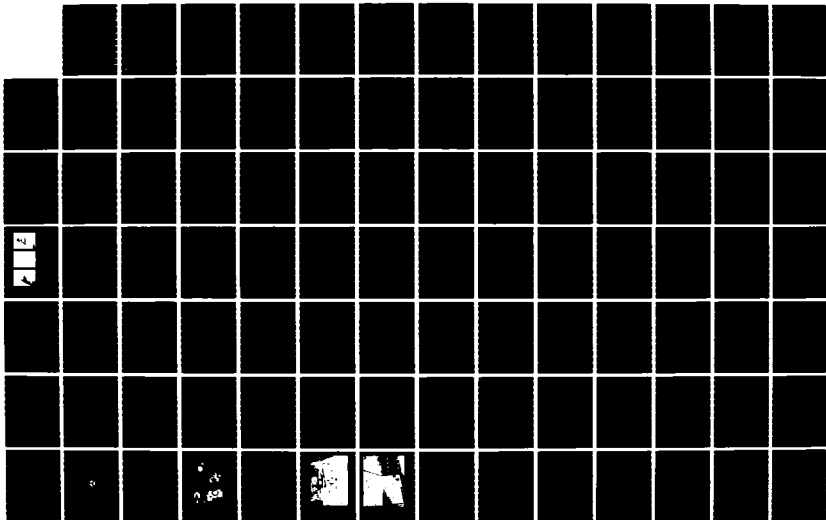
PROCEEDINGS OF FUEL SAFETY WORKSHOP HELD AT ALEXANDRIA  
VIRGINIA ON 29 OCT. (U) FEDERAL AVIATION ADMINISTRATION  
WASHINGTON DC PROGRAM ENGINEE.. 31 DEC 85  
DOT/FAR/PH-86/13

1/4

UNCLASSIFIED

F/8 21/4

NL





✓  
DOT/FAA/PM-86/13 ✓

Program Engineering &  
Maintenance Service  
Washington, D.C. 20591

②  
**Proceedings of Fuel Safety Workshop**

**October 29-November 1, 1985  
Ramada Inn, Seminary Rd.  
Alexandria, Virginia**

**AD-A168 784**

Compiled by  
Analysis Group, Inc.  
400 15th Street, S.W.  
Washington, D.C. 20003

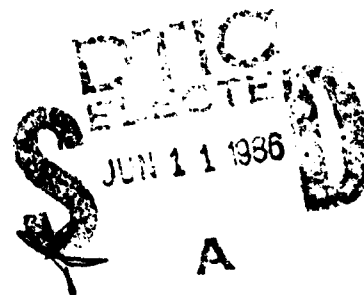
December 31, 1985

This document is available to the public  
through the National Technical Information  
Service, Springfield, Virginia 22161.



U.S. Department of Transportation  
Federal Aviation Administration

**NTC FILE COPY**



86

0 10 005

# **NOTICE**

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

Technical Report Documentation Page

1. Report No. DOT/FAA/PM-86/13		2. Government Accession No. <b>AD-A168784</b>		3. Recipient's Catalog No.	
4. Title and Subtitle <b>PROCEEDINGS OF FUEL SAFETY WORKSHOP</b> October 29 - November 1, 1985				5. Report Date <b>December 31, 1985</b>	
				6. Performing Organization Code	
7. Author(s) <b>Compiled by Analysis Group, Inc. Washington, D.C.</b>				8. Performing Organization Report No.	
9. Performing Organization Name and Address <b>Department of Transportation Federal Aviation Administration, APM, Aircraft Safety &amp; Airport Technology Division Washington, D.C. 20591</b>				10. Work Unit No. (TRIS)	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address <b>Department of Transportation Federal Aviation Administration APM, Aircraft Safety &amp; Airport Technology Division Washington, D.C. 20591</b>				13. Type of Report and Period Covered <b>Proceedings</b>	
				14. Sponsoring Agency Code <b>APM-700</b>	
15. Supplementary Notes <b>* Held at Ramada Inn, Seminary Rd., Alexandria, Va.</b>					
16. Abstract <p>The approximately 150 participants attending the Fuel Safety Workshop sponsored by the Federal Aviation Administration, all made valuable contributions to the successful exchange of information. The four-day workshop, held October 29 through November 1, 1985, provided representatives from airline operations and management, manufacturers, suppliers, governments and private sector organizations a forum to constructively review the state-of-the-art in fuel safety research.</p> <p>The workshop served a four-fold purpose: 1) To discuss the results from the FAA/National Aeronautics and Space Administration (NASA) Controlled Impact Demonstration (CID) conducted last December at Edwards Air Force Base, California; 2) To explore potential approaches to preventing post-crash aircraft fuel fires, including possible combinations of various approaches; 3) To re-evaluate past approaches in terms of current technology; and 4) To propose a course of action for future industry/government research, especially any future FAA Research and Development program.</p> <p>These Proceedings contain the formal Conference presentations followed by the recommendations of the attendees as agreed upon in the three informal working breakout sessions.</p>					
17. Key Words <b>Proceedings      Fuel Research Aircraft Fuel Fires Post-Crash Fire Hazard Fire Prevention Controlled Impact Demonstration</b>			18. Distribution Statement <b>This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.</b>		
19. Security Classif. (of this report) <b>UNCLASSIFIED</b>		20. Security Classif. (of this page) <b>UNCLASSIFIED</b>		21. No. of Pages <b>386</b>	
				22. Price	

## TABLE OF CONTENTS

Page

### OPENING SESSION

INTRODUCTION BY WORKSHOP CHAIRMAN: Mr. Donald A. Schroeder, Manager, Aircraft Safety Program, FAA . . . . .	1
WELCOME TO ATTENDEES: Mr. Neal A. Blake, Deputy Associate Administrator for Engineering, FAA . . . . .	3
KEYNOTE ADDRESS: The Honorable Norman Y. Mineta, Chairman, Subcommittee of Aviation, Committee on Public Works and Transportation, U.S. House of Representatives . . . . .	5

### SESSION I: FUELS RESEARCH - FAA

CHAIRPERSON: Mr. Bruce Singer, Manager, Aircraft Safety & Airport Technology Development Division, FAA . . . . .	9
ANTIMISTING FUEL TECHNOLOGY: Mr. Eugene Klueg, FAA Fuels Project Engineer, FAA . . . . .	11
AMK FULL-SCALE TRANSPORT AIRCRAFT VALIDATION PHASE SUMMARY: Mr. Bruce Fenton, CID Project Engineer, FAA . . . . .	61
POST CONTROLLED IMPACT DEMONSTRATION (CID) ANALYSIS: Mr. William Westfield, Manager, Engine/Fuel Safety Branch, FAA . . . . .	115
FUEL CONTAINMENT RESEARCH AND DEVELOPMENT: Mr. Lawrence Neri, Crashworthiness Project Engineer, FAA . . . . .	137
LUNCHEON GUEST SPEAKER: Mr. John H. Enders, President, Flight Safety Foundation, Incorporated . . . . .	149

### SESSION II: FUELS RESEARCH - GOVERNMENT

CHAIRPERSON: Dr. Homer Carhart, Naval Research Labs . . . . .	157
ANTIMISTING FUEL BREAKUP AND FLAMMABILITY: Dr. V. Sarohia, JPL AMK Program Manager, Jet Propulsion Laboratory . . . . .	159
U.K. PROGRAM ON SAFETY FUELS: Dr. S.P. Wilford, Royal Aircraft Establishment . . . . .	163
HEAT TRANSFER, FRICTION, AND RHEOLOGICAL CHARACTERISTICS OF ANTIMISTING KEROSENE: Dr. V. Sarohia . . . . .	181

U.S. ARMY FIRE SAFETY PROGRAM: Mr. F.W. Schaekel, Chief, Fuels & Lubricants Branch, U.S. Army . . . . .	185
CONTINUOUS INLINE BLENDING OF ANTIMISTING KEROSENE: Dr. P. Parikh, UPL AMK Technical Staff, Jet Propulsion Laboratory . . . . .	203
AMK RHEOLOGY AND QUALITY CONTROL: Dr. Richard Mannheimer, Southwest Research Institute . . . . .	N/A

### SESSION III: FUELS RESEARCH - INDUSTRY

CHAIRPERSON: Dr. Alan E. Zengel, Coordinating Research Council, Inc. . . . .	219
OLEFIN POLYMERS AS JET FUEL ANTIMIST ADDITIVES: Mr. Steve Baxter, Conoco, Incorporated . . . . .	221
AMK - STILL VIABLE?: Mr. Charles Rivers, ICI Americas, Inc. . . . .	241
AIRLINE PERSPECTIVE ON SAFETY FUELS: Mr. Dick Tobiason, Air Transport Association of America . . . . .	251
SAFETY FUEL SPECIFICATIONS: Mr. Tom Peacock, Senior Staff Engineer, McDonnell Douglas Corporation . . . . .	255
DESIGN PROCEDURES FOR MINIMIZING POST CRASH FIRE HAZARDS: Mr. Howard Skavdahl, Boeing Aircraft Company . . . . .	261

### SESSION IV: FUELS RESEARCH - PRIVATE/UNIVERSITY

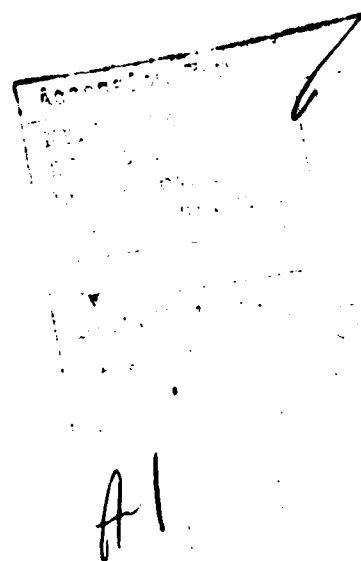
CHAIRPERSON: Dr. Martin Summerfield, Princeton Combustion Research Labs . . . . .	277
AMINE-CO <sub>2</sub> ADDUCTS AS AVIATION FUEL GELLING AGENTS: Mr. William Bannister, President, Aviation Fuel Safety Company . . . . .	279
CRASH SAFETY FUEL TANK: Mr. Allen Tansill, Consultant . . . . .	299
GTA/BASF ANTIMISTING FUEL RESEARCH: Mr. Jerry Trippe, Executive Vice President, General Technology Applications, Inc. . . . .	301
FIRE PREVENTION ON AVIATION FUELS, DUE TO ACCIDENTAL SPILLAGE OR IMPACT CONDITIONS: Mr. Robert Bayless, President, Capsulated System, Incorporated . . . . .	313
JET FUEL VISCOSITY AT LOW TEMPERATURES WITH NOTES ON n-ALKALINE CRYSTALS: Professor Dale Schruben, Department of Chemical Engineering, University of Akron, Ohio . . . . .	317
AUTOMATIC FUEL JETISON SYSTEM: Professor A.D. Kriech, University of Michigan, Ann Arbor, Michigan . . . . .	357

## WORKING GROUP MEETINGS

WORKING GROUP GUIDELINES: Mr. Donald A. Schroeder . . . . .	361
REPORTS OF WORKING GROUPS: Presentation of recommendations by chairpersons of working groups . . . . .	363
SUMMARY OF WORKING GROUPS RECOMMENDATIONS: . . . . .	371
APPENDIX A: BIBLIOGRAPHIES OF PRESENTORS . . . . .	373

## ATTACHMENTS

Bibliographies  
List of Attendees  
List of Speakers



Al



OPENING SESSION

## INTRODUCTION

Mr. Donald A. Schroeder  
Program Manager, Aircraft Safety Research and Development Program  
FAA Headquarters

Good Morning! I would like to welcome you to Alexandria, Virginia and our Fuel Safety Research Workshop. I trust you enjoyed last night's reception and are all registered and have your conference package. If not, the registration desk will be available at the break and during lunch.

We have arranged a program that I think you will find both informative and interesting.

Later this morning, after our Keynote Address by Congressman Norman Mineta, the FAA will discuss our Fuel Safety Research Program and what occurred last December at our Controlled Impact Demonstration.

At today's luncheon, we are honored to have Mr. Jack Enders from The Flight Safety Foundation to discuss Safety Procedures in our aviation industry.

At the remainder of today's sessions we will hear from both Government and industry speakers. They will discuss past and current fuel safety research programs.

Tomorrow we will hear from the private and university sector. After lunch tomorrow, the three workshops will convene, and conduct a discussion of new ideas/activities, etc. On Friday morning the workshops will report on their findings to the entire group. We expect to adjourn around noon on Friday.

On Thursday morning, prior to the break outs, I will give you more details on what is expected in the workshops. Because of the unbalance in numbers and since some individuals expressed an interest in more than one subject area, we decided to hold three parallel sessions. Each session will discuss all fuel safety initiatives.

At this time I would like to introduce Mr. Neal Blake, the Deputy Associate Administrator for Engineering in the Office of Development and Logistics.

## WELCOME TO ATTENDEES

Neal A. Blake  
Deputy Associate Administrator for Engineering,  
FAA Headquarters

Good Morning Ladies and Gentlemen!

I would also like to add my welcome to you to our Fuel Safety Research Workshop.

The FAA has conducted many research and development programs aimed at reducing or eliminating the post-crash fire hazard. These efforts have resulted in a number of actions, including issuance of advisory circulars, rules, and notices of proposed rulemaking, covering safety improvements in aircraft. Recent activities have involved seat fire blocking layers to reduce flammability and to extend evacuation time, improved cargo compartment liners, improved emergency evacuation lighting systems and improved criteria and test methods for selecting cabin materials.

In one area, however, we have yet to identify a fully satisfactory solution. That area is development of a suitable method of containment or treatment of aircraft fuels that will reduce or eliminate the threat of post-crash fuel fires.

The FAA has conducted research activities in this area since the early 1960's. In 1964 FAA initiated a research effort to develop a modified fuel which could be used in routine flight operations and also be capable of reducing the fire hazard during survivable impacts by:

- Decreasing the probability of fuel ignition,
- Reducing flame propagation rates, and
- Eliminating the mist of combustible vapors.

This research produced the highly viscous gelled fuels of the late 1960's and early 1970's. Although the fire reduction characteristics of these fuels were good, there were many difficult and compatibility problems with the engines, aircraft fuel systems and ground refueling systems.

In 1972, new high molecular - weight polymer fuel additives were developed which provided fire suppression characteristics comparable to these of gelled fuels. Our efforts from 1974 through 1978 were directed toward developing a better understanding of the characteristics of fuels produced using these additives.

During this period a Memorandum of Understanding was signed between the United States and the United Kingdom defining a cooperative program to determine the feasibility of developing antimisting fuels using a British developed Antimisting Kerosene (AMK) additive. The principal participants of this program were the Federal Aviation Administration (FAA), the Royal Aircraft Establishment and the National Aeronautics and Space Administration.

The antimisting fuel technology was developed under this program to the point where full-scale testing could be conducted. Many of the technical problems were solved and the Boeing 720, used in the Controlled Impact Demonstration (CID) flew successfully using the treated fuel. The degree of fire protection provided by the fuel in the CID test, however, was judged to be inadequate for FAA to proceed with rulemaking at this time.

Evaluation of CID results did show evidence of antimisting action and reduced heat transfer to the fuselage. The impact scenario achieved at Edwards - which we believe was unique in that it differed from previous survivable accidents we have studied - demonstrated that there are conditions where adding an antimisting characteristic to jet fuel is not sufficient to prevent a post-crash fuel fed fire. Specifically, the destruction of an engine, and the rupture of degraded AMK fuel, hydraulic and oil lines produced an intense ignition source at the point of fuel release.

Over the next several days the results of government sponsored research activity in the fuels area will be presented along with the CID results. Following this, industry, user, academia and private views on alternative methods of fire reduction or prevention will be explored.

As Don mentioned, several working groups are planned to review the material presented and to develop recommendations that can be used by the FAA to determine potential areas of research that may provide answers to the post-crash fire threat. Our conference is designed to give you the opportunity to provide us with your best thoughts and ideas and help us in the formulation of our future program in this important area.

To introduce our conference today we are extremely honored to have as our Keynote Speaker the Honorable Norman Mineta, Chairman, Subcommittee on Aviation, of the Committee on Public Works and Transportation, House of Representatives.

## KEYNOTE ADDRESS

### REMARKS OF HONORABLE NORMAN Y. MINETA TO THE FUEL SAFETY RESEARCH WORKSHOP

Chairman, Subcommittee on Aviation  
U.S. House of Representatives

I am very pleased to be here with you this morning as you begin your Fuel Safety Workshop. It is gratifying to see such an international mix of industry, university and government experts who have gathered here to assess where we have been and where we want to go in our research of fuel safety issues.

Improving fuel safety has long been an important component in looking beyond accident prevention at ways to maximize the survival of airline passengers. Many of you have been closely involved in the development and testing of anti-misting agents in Jet-A kerosene as one possible solution to the problem of fire on impact. For many, this research was to culminate in the Controlled Impact Demonstration conducted jointly last fall by FAA and NASA, with the support of NTSB, the Department of Defense and the British and French governments.

The actual outcome of that test and the subsequent analyses of its data will be debated for a long time to come. However, one conclusion is perfectly clear. It was summed up in a letter I recently received from FAA Administrator Don Engen, and I quote, "The AMK concept is not practical for day-to-day airline operation in the foreseeable future."

In its own way, Admiral Engen's conclusion should serve as both good and bad news. The bad news being obviously that AMK is not the problem-solver we had hoped it would be. The good news is the clear signal from the top to continue your search for workable solutions to these safety problems. Since our lives literally depend on it, you must maintain the forward momentum that has been established in this research. When in need of encouragement, remember that it wasn't too many years ago when it was difficult to get industry or government to even accept the idea that crash survivability was worthy of consideration and in need of improvement. From your good work, we have mounted and passed that hurdle.

I would like to shift now from your undoubted area of expertise to the broader view I get on aviation safety from the chairmanship of the House of Representatives Aviation Subcommittee. From that seat, I can report some regulatory movement to improve aviation safety. However, I am still seriously bothered by what I consider to be a lack of concern or an attitude of complacency, particularly on the part of the Administration.

I must underscore that when the Congress deregulated the airlines in 1978, it was never our intent to deregulate safety. This becomes even more important in light of the number of tragic aviation accidents we have had this year. Thus far, no apparent common link or thread has been established between these accidents but I believe they individually point to a number of areas where improvements are needed.

Specifically, I want to address three such areas where improvements are needed. The first of these concerns cabin safety and crash survivability standards. The second involves the FAA's ability to proceed with the necessary research, development, and deployment of critical weather radar technology. The third area is FAA's air carrier safety inspection program.

With regard to the first, last year, after more than a decade of hearings and promises of regulatory actions, legislation was introduced that would have set specific deadlines for FAA's issuance of a number of regulations on cabin safety and crash survivability. In the face of this pending legislation, during another series of hearings, the FAA Administrator agreed to follow a specific timetable for regulatory action and to report monthly to Congress on the progress of those actions without a legal mandate to do so.

We are now seeing positive results and Admiral Engen is to be commended for his leadership on these matters. In the past year, we have seen the issuance of three rules that we consider important to improving cabin safety. One rule calls for the entire U.S. airline fleet to be equipped in the next two years with seat cushions that are more fire retardant. The second calls for, within a little more than a year, equipping the fleet with emergency floor markings aimed at improving visibility for escaping passengers in a dark, smoke-filled cabin. Thirdly, by next spring, we will have additional and improved fire extinguishers and smoke detectors in airplanes.

Along with this progress, however, I still see resistance, particularly in the area of flammability standards for other cabin materials. I share the frustration of many of my Congressional colleagues when I hear the continuing debate about which materials, if any, would improve cabin safety in a fire. You and I both know that there are presently materials on the marketplace that are superior in fire retardancy and toxicity to the materials presently used in most airline cabins. These materials are being used in newer aircraft like Boeing's 757's and 767's and MD-80's.

Although these materials have trade offs and are not the perfect or ultimate solution, they are clearly better than what is on-board most of the fleet now. I ask you then what is the reason for not requiring their use if they can indeed save lives? While I do not question the need for actively continuing our research efforts to find the best possible solutions, I can neither condone nor accept ignoring or holding in abeyance what is clearly better and readily available.

I would like to shift now to a circumstance where budgetary policy, rather than technology, has interfered with the development and deployment of potentially life-saving weather radar. The recent Delta accident in Dallas, where 135 people lost their lives, if the preliminary findings bear out, is a tragic underscoring of my point. We know that wind shear has been identified by the NTSB as the major cause of at least 16 airline accidents since 1970. In countless other incidents, many close calls can also be attributed to the wind shear or microbursts commonly associated with thunderstorm activity.

Yet the Administration, through the Office of Management and Budget, has deliberately tried to slow down the Next Generation Radar (called NEXRAD) and, by association, terminal Doppler radar, both of which will be instrumental in hazardous aviation weather detection. I am greatly concerned that the Administration will continue to try to delay or stop on-going funding for the development of these two radar improvements; programs I consider of critical importance to preventing the future loss of airline passengers' lives to wind shear.

I will be holding hearings on this later today. You can be sure I will do all I can to keep the pressure on to continue this research and development. In this regard you should note that the funds for NEXRAD and the terminal Doppler program may be found in the \$3.3 billion surplus now sitting in the airport and airway trust fund. Suffice it to say here, we are working to get the trust fund removed from the unified budget so the users can get what they have been paying for since 1982.

The third and final safety area I would like to address relates to FAA's air carrier maintenance and operations inspection program.

Given the dramatic increase in the number of airlines since deregulation and the ensuing fundamental changes that airline operations have been undergoing, I have become increasingly alarmed at FAA's failure to keep pace and reflect these changes in the number of its safety inspectors. Not only have there been no staff increases; in 1983, the Administration actually cut the number of inspectors by approximately 25 percent. I held hearings then and subsequently the Secretary of Transportation restored the number of inspector positions to 674.

However, my concern has continued, particularly with FAA's grounding of several airlines last year. The FAA cited long-standing problems as the reasons for grounding. I found this particularly troublesome and questioned the adequacy of ongoing inspection and surveillance. How good could their inspections be if things had gone so far that grounding airlines was the best response?

As a result of these concerns and the results of a GAO study which found that some airlines were receiving virtually no inspections, I offered an amendment to the Fiscal Year 1986 Department of Transportation Appropriations bill that called for the addition of 200 FAA safety inspectors and 100 support personnel. I am pleased to note that my amendment was adopted by the House last month. I also intend to push for an additional 150 inspectors and 50 support personnel next fiscal year.

In a matter of days after adoption of my amendment by the House, the Secretary of Transportation announced a "major safety initiative" which called for adding 200 inspectors and 100 support personnel in 1986 and 150 inspectors and 50 support personnel in 1987. Secretary Dole went on to say that she would be requesting these funds from OMB.

Of course, I do not have a problem with the Administration finally coming around to recognize and act on these important safety issues. My concern, however, is the length of time and the degree of effort it takes to make them acknowledge what is so obvious to others. Most importantly, this time and effort may be costing lives.

No doubt, we have all heard that one current obstacle to rulemaking in the safety field has been the Administration's insistence on considering whether a proposed rule is cost effective and on assessing the willingness of the American public to pay for added safety. I have a healthy respect for the need to consider cost. But when cost considerations become a vehicle for holding up needed safety actions -- especially when we have the money in the trust fund and the people have already paid -- I think we must seriously question the validity and wisdom of these hold-ups.

Before closing, I must share one of my frustrations with you and urge you to not inadvertently resist and delay the development of needed safety initiatives. As engineers and research and development experts, you are trained to search for the perfect solution to a present problem, whatever it may be. Your charge, most immediately in the next four days, as well as in the long-range future, will be to come up with solutions minimizing the potential of death by fire in otherwise survivable aviation accidents. Through additives, isolation or containment, or some combination of these, you will be working to improve fuel safety.

In this work, you must be careful not to become a party to resistance while trying to achieve the perfect solution. To do so, would be to allow to happen what the French political philosopher Voltaire must have had in mind when he wrote, "... the best is the enemy of the good . . ." It is imperative that we not let our search for the best allow us to be blinded to the good, and to overlook intermediate workable solutions. This is as true for the policy solutions I seek, as it is for the technical solutions for which you search.

I will continue to do my part to insure that the points of resistance to safety are prodded and that aviation safety stays in the forefront of the minds of both regulators and the industry. In turn, you must do your part to make sure that workable solutions to aviation safety problems stay in the forefront of your minds and work.

Thank you for the opportunity to speak with you this morning and I wish you much success during your workshop.

SESSION I: FUELS RESEARCH - FAA  
Chairperson: Mr. Bruce Singer

## ANTIMISTING FUEL TECHNOLOGY FOR TRANSPORT CATEGORY AIRCRAFT

E. P. KLUEG

FEDERAL AVIATION ADMINISTRATION

The survivability of aircraft occupants in jet transport crashes can be significantly enhanced by minimizing post-crash fire hazards. One of the greatest dangers is the fireball resulting from ignition of spilled fuel during the crash deceleration. Frequently, in an impact-survivable crash, fuel tanks rupture and large amounts of fuel are released while the aircraft is still in motion. Under these conditions, fuel sheared by the airstream forms a highly flammable mist which is easily ignited by engine surges, hot engine components, electrical or frictional sparks generated crash-related ignition sources. These mist ignitions are explosive and, typically, the fire propagates to the fuel release locations, flames become attached to the aircraft, and fuel in and pooled around the damaged aircraft ignites as it comes to a rest. In such crashes, approximately 30 percent of the fatalities are a direct result of fire or the resulting heat, smoke, and toxic gases. Thus, impact-survivable aircraft crash landings can become major disasters as a result of the fire fatalities and property loss.

Research efforts initiated in 1964 by the Federal Aviation Administration (FAA) produced the highly viscous gelled fuels of the late 1960's and early 1970's (1). Although the fire reduction characteristics of these fuels were good, the engine and aircraft fuel system and ground refueling system compatibility problems were severe. In 1972, new antimisting kerosene (AMK) fuels were developed consisting of 0.2 to 0.5 percent high molecular weight polymeric additives with viscosities approaching those of conventional fuels. When released from a ruptured fuel tank during a crash, antimisting kerosene fuels are designed to break up into very coarse sprays or sheets, rather than the usual fine mist. This coarse breakup slows ignition of any pooling fuel, thereby providing additional time for occupants to escape.

Public hearings in 1977 prompted the FAA to reexamine the status of antimisting fuel technology. Results of ongoing research in the United States (U.S.) and in the United Kingdom (U.K.) were encouraging. As a result, the FAA Antimisting Fuel Program was greatly expanded in 1978 under a Memorandum of Understanding (MOU) between the U.S. and the U.K. The two countries agreed to cooperate in determining the feasibility of introducing antimisting fuel into civil aviation. It was recognized at that time that AMK was a high risk, but a high payoff program and not cost beneficial in the classical sense.

The principle participants under the MOU were the FAA and the Royal Aircraft Establishment (RAE) of the U.K., with the National Aeronautics and Space Administration (NASA) as a third party to undertake basic research and provide technological support. The British-developed additive which showed the

greatest promise at the time was manufactured by Imperial Chemical Industries (ICI Americas and ICI Limited) and was a high molecular weight, hydrocarbon polymer termed FM-9™.

A Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee was established by the FAA in 1978 to consider all programs to increase probability of survival in fire-related accidents. The SAFER Committee concluded (2) that AMK could provide the single, most significant, safety improvement to reduce the post-crash fire hazard and recommended continuing and expanding AMK research because of the substantial reductions in the fatality rate that could be produced.

#### FAA ANTIMISTING FUEL PROGRAM

In conjunction with the MOU, the FAA developed a 6-year phased program (3) to accomplish the following:

- a. determine the feasibility of using antimisting fuel,
- b. develop recommendations as to the introduction and use of antimisting fuel,
- c. demonstrate the effectiveness of antimisting fuel in a crash, and
- d. assess the economic reasonableness in support of regulatory actions.

The basic program utilized the FM-9™/Jet A AMK fuel as a representative agent to prove the concept of using such fuels. FM-9 development was frozen during the initial feasibility phase of the program to provide a fixed data base for evaluating the overall antimisting concept.

The U.S./U.K. Management Committee on Antimisting Kerosene Fuel concluded in November 1980 that AMK was feasible, that benefits exist in the form of greatly increased resistance to post-crash fuel mist fire, and that none of the problems uncovered at that time were regarded as technically unsolvable. The Committee agreed to a continuation of the joint MOU and endorsed research efforts leading to full-scale ground and flight tests, culminating in a crash demonstration in the 1984 time period.

The FAA contracted with the Aerospace Corporation to assess the economic aspects of converting the world, turbine-powered, commercial aircraft fleet to antimisting kerosene fuel. This preliminary assessment (4) of the costs and benefits associated with converting to AMK, indicate that the added cost of fuel due to the addition of the antimisting additive was by far the largest cost. The total worldwide cost over an assumed 20-year useful lifetime of the investment was calculated to be \$15.5 billion, based on a 6.9¢ additive cost per gallon of fuel as an upper limit. This total worldwide cost is reduced to \$4.5 billion for a 1.0¢ additive cost per gallon of fuel. The FM-9 additive represents 83 percent (\$12.9 billion) of this total cost. It was determined that an increase of 2 to 3 percent in the price of an airline ticket (based on the 6.9¢ additive cost) would cover the additional costs associated with converting and operating on AMK fuel.

The Aerospace Corporation study also estimated that an average of 135 preventable fatalities have occurred each year during the last decade as a result of aircraft accidents involving post-crash fires. The British Civil Aviation Authority (5) estimated that 5,000 fatalities will occur during the 1976 to 1990 time period, due to post-crash fire in otherwise survivable accidents.

The FAA also contracted with the B&M Technological Services, Inc. (6), to generate a data base and methodology for analyzing the potential impact of introducing AMK into the U.S. commercial fleet. Analysis indicated that fleet-wide introduction would maximize the benefit in terms of increased safety. However, segmental introduction would be preferable in terms of lower costs and potential capacity constraints. The large number of two-engine, regular-body, turbofan aircraft in the fleet, combined with a relatively low cost impact, suggested that these aircraft may be the best candidates for early introduction of antimisting fuel.

The antimisting fuel accomplishments under the MOU and the FAA program during the last 7 years can be categorized as AMK characterization, flammability, production, compatibility, flight tests, and impact demonstration.

#### AMK CHARACTERIZATION

Under certain conditions, FM-9 antimisting kerosene behaves as a non-Newtonian fluid with complex rheological characteristics. In order to understand and predict the characteristics of AMK, FAA undertook an extensive rheological study. In addition to work on AMK characterization at the FAA Technical Center, the FAA sponsored research at Southwest Research Institute (SWRI), NASA's Jet Propulsion Laboratory (JPL), and United Technologies Corporation's Pratt & Whitney Aircraft (PWA). Initial research efforts focused on determining the rheological characteristics of undegraded AMK (high resistance to misting) that were responsible for antimisting behavior.

Early rheological experiments at JPL and SWRI with capillary tube viscometers showed that the shear viscosity of FM-9 AMK increased suddenly when a critical shear rate was exceeded (7,8). This increase in shear viscosity, however, was not large enough to account for AMK's ability to resist atomization at air speeds of 150 knots and higher. Later work indicated that extensional viscosity generated in AMK as a result of normal stresses is the dominant rheological characteristics responsible for mist prevention.

The FAA, JPL, and SWRI have developed methods to quantify the viscoelasticity of undegraded AMK for use as a quality control test of antimisting effectiveness. The die swell technique, developed to measure the expansion of a jet as the AMK flows out the end of a capillary tube, shows the most promise as a real-time quality control test (9,10). This test should have a better physical and theoretical relationship to AMK's antimisting behavior than the orifice flow cup test, which was the primary quality control test developed by ICI for undegraded AMK.

The FAA and FAA contractors have also worked on the development of more precise methods for characterizing highly degraded FM-9 AMK (low resistance to misting). The degradation level of AMK is considered a reliable indicator of AMK's filterability and combustibility. The standard procedure for quantifying the level of degradation was a filter ratio test. This test is a ratio of the time required for a known quantity of test fuel to flow through a specified filter, to the time required for the same quantity of Jet A fuel. The filter ratio test lacks the sensitivity needed for reliable indications of filterability of very highly degraded AMK. Consequently, other methods for evaluating the properties of highly degraded AMK were investigated.

SWRI developed a small-scale, pump filtration test to simulate filtration conditions in an aircraft fuel system and to measure the filter plugging characteristics of intentionally degraded AMK (10). The FAA, SWRI, and PWA evaluated gel permeation chromatography (GPC) as a characterization test for highly degraded AMK (11,12,13,14). GPC was able to discriminate among different samples of highly degraded AMK. However, GPC was not able to predict the filterability of highly degraded AMK containing small amounts of undegraded FM-9 polymer.

SWRI also developed a simultaneous filtration/degradation test that shows promise as a quality control test of inline blended, highly degraded AMK (15). Utilizing this test, SWRI has found that freshly blended AMK is only slightly more resistant to degradation than fully equilibrated AMK and develops satisfactory mist-fire protection within 30 minutes of blending.

FAA contractors also made a detailed study of the heat transfer properties of AMK to insure that aircraft and engine heat exchanger performance would be adequate. PWA results (13,14) show that at low flow rates, the heat transfer coefficients of degraded AMK and Jet A were nearly identical. At higher flow rates, the degraded AMK was about 10 percent lower than Jet A but still considered marginally acceptable for use in engine heat exchangers. PWA considered the heat transfer characteristics of undegraded AMK unacceptable for use in such engine components.

JPL undertook generalized flow and heat transfer experiments to define the flow behavior of FM-9 AMK (16). JPL concluded that the flow and heat transfer behavior of AMK can be divided into three regions: Newtonian laminar region, shear-thickening transition region, and drag reducing turbulence region. At low flow rates, undegraded AMK behaves as a Newtonian fluid with constant viscosity for a given temperature and has a heat transfer coefficient equivalent to that of Jet A. At a certain critical shear rate, shear thickening occurs and causes a large increase in skin friction and heat transfer rates. This shear thickening region was not observed in low polymer concentrations or in partially degraded AMK. In the drag reducing turbulent region, the skin friction and heat transfer rates dropped rapidly, falling below the predicted Newtonian values and resulting in a lower heat transfer capability than Jet A.

## AMK FLAMMABILITY

Rheology also plays a dominant role in the antimisting performance of AMK. The major effect of the FM-9 antimisting additive on jet fuel flammability is the formation of large droplets, which are more difficult to vaporize and ignite than the fine mists produced by unmodified Jet A. The FAA and FAA contractors have developed several test facilities to measure the flammability characteristics of antimisting fuels under various simulated takeoff and landing conditions.

While all the flammability tests provided meaningful information, the FAA's large-scale, wing-fuel spillage test (17) appears to be the most realistic in simulating the conditions encountered by jet fuel in impact-survivable accidents. A high volume airflow flows over a wing section at speeds up to 200 knots. Nominally, 85 gallons of AMK from a pressurized tank is discharged at 20 gallons/second through an orifice in the leading edge of the airfoil. A propane torch serves as the ignition source, and high speed cameras record ignition and flame propagation characteristics.

FAA researchers have conducted more than 300 tests on the wing-fuel spillage rig and have developed an ignition envelope for AMK as a function of FM-9 concentration, airspeed, fuel spillage rate, ambient air temperature, fuel temperature, and location, type and intensity of the ignition source (17,18). The results from these tests show that a 0.3 percent concentration of FM-9 in Jet A will prevent the formation of mist-generated fireballs at speeds up to 150 knots. Unlike Jet A fuel, even at simulated airspeeds above 150 knots, AMK propagation was relatively slow, and the flames did not propagate upstream to the simulated ruptured tank.

To validate the results from the wing-fuel spillage tests, the FAA conducted a series of large-scale, catapult crash tests with surplus military aircraft at the Naval Air Engineering Center (19,20). The results from the catapult crash tests showed good correlation with the wing-fuel spillage tests.

Small-scale flammability tests are generally effective for initial screening of antimisting fuels, but do not correlate well with each other nor with large-scale tests (21). Small-scale flammability devices developed for AMK investigations include the FAA Flammability Comparison Test Apparatus (22), the SWRI Spinning Disk (11), the JPL Miniwing Shear Apparatus (23), and liquid breakup analysis by image enhancement.

The JPL Miniwing Shear Apparatus has provided a controllable means of generating fuel sprays for photographic analysis. The results of this work show that the AMK droplet size decreases with increase in airspeed. These experiments indicate that AMK mist flammability is a function of the effective Sauter Mean Diameter (SMD) of the fuel droplets. AMK-air mixtures containing fuel droplets with an SMD of 500 microns or less will produce self-sustaining flames.

JPL also investigated the flame spread rate across a pool of AMK. Test showed no significant differences in the flame spread rates of Jet A and FM-9 AMK. In tests with a porous substrate, the flame spread rate for AMK was slightly lower than for Jet A.

#### AMK PRODUCTION

Early in the AMK program, researchers recognized the desirability of blending antimisting additives into jet fuel at the aircraft fueling point (24). Introduction of the additive at an earlier stage would increase costs, unintentional degradation, and the possibility of contamination (25).

A high FM-9 additive solid content dispersion in a carrier fluid was developed by ICI to achieve the one-step introduction of FM-9 into the fuel at the aircraft fueling point (26). A carrier fluid consisting of a glycol and an amine was found to produce a slurry having the best overall properties.

The FAA sponsored work to develop and optimize in-line blending of AMK, included investigations at JPL (27,28). JPL developed in-line blenders using a static mixing tube system concept. The blenders are simple, two-stage, continuous flow systems in which the slurry is introduced into the fuel in the first stage while the second stage enhances mixing. The blending occurs during three phases: metering, dispersion, and dissolution. The precise, continuous, metered flow of slurry into the metered Jet A flow results in the dispersion of the slurry in the fuel. The dispersion is completed and the dissolution initiated by the use of static mixing tubes immediately after the slurry is metered into the Jet A. The mixing tubes generate a radial swirl to mix the constituents into a homogenous blend. As the FM-9 becomes completely dispersed throughout the Jet A fuel, the polymer swells to form a stable solution as the mixture equilibrates. The physical characteristics of the blend change during the dissolution phase. Initially, the blend has a very cloudy appearance that becomes clear within 15 to 30 minutes.

The blending equipment has evolved from a small, laboratory-scale, one liter/minute unit (27) to a 5 to 10 gallon/minute (gpm) unit (28) used to support a CV880 flight test program. Next came a 10 to 50 gpm unit (29) used for a fuel tank environmental investigation (30) and a 50 to 125 gpm units (29) used in the B720 Controlled Impact Demonstration Program (31). Miniwing fire tests at JPL and wing-fuel spillage tests at the FAA Technical Center were used to monitor and insure the quality of the fuel produced by the large blenders.

In blending studies by the RAE and JPL (1,27), freshly in-line blended FM-9 AMK fuel developed adequate fire resistance after a 15- to 20-minute aging period provided that the blend temperature and the aromatic content of the base fuel were not too low. The polymer particles tend to settle out from the blend when the fuel blending temperature was below 0 degrees Celsius and the aromatic content of the base fuel was less than 12 percent.

ICI has been working on improvements to increase the solid content of the slurry and the dissolution rate of the FM-9 polymer in jet fuel. .

March 1983, ICI developed a new slurry with a higher solid loading that had excellent dissolution properties. The AMK fuel successfully demonstrated fire resistance properties and degradability within 15 minutes of blending. However, this material was available in only limited quantities and was not utilized in the full-scale validation phase of the FAA program.

The FAA sponsored studies at JPL on the effects of different base fuels on the properties and performance of the antimisting fuels (27). Significant compositional differences in Jet A base fuels were found; but, with the exception of the aromatic content lower limiting factor, these variations did not significantly alter the AMK characteristics.

PWA's assessment of the use of AMK fuel in engines included an investigation to determine the compatibility of several approved Jet A fuel additives with AMK (13,14). The anti-icing additive was the only additive to produce a precipitate in AMK at the maximum allowable concentration. Further evaluations must be conducted to understand fully the compatibility of approved Jet A additives with AMK fuel as well as whether the need for such additives exists in conjunction with AMK fuel. Since FM-9 AMK fuel has better lubricity properties than Jet A and contains approximately one percent glycol, lubricity and anti-icing additives may no longer be required.

A number of investigations have been performed to determine the effects of liquid water and water vapor on AMK fuel (32,33). The addition of liquid water will make fuel cloudy and can cause a white sticky precipitate to settle out of the fuel. Therefore, the introduction of bulk water into aircraft fuel systems must be prevented by improved fuel handling practices. The technology exists to control the presence of bulk water in Jet A fuel during the blending process and subsequent fueling of the blended AMK into the aircraft tanks. Operational experience shows that water is not introduced into aircraft fuel tanks in bulk quantities except by careless fuel handling procedures.

Water from condensation and coalescing of dissolved water led to a concern for the use of FM-9 AMK under operational conditions. However, as will be discussed in the Compatibility Section of this report, further studies have shown that, aside from accidental introduction of bulk water, FM-9 AMK is expected to be free of water reactive problems.

Initial in-line blending experience under the FAA program resulted in problems caused by poor polymer dispersion, slurry property variations, Jet A fuel variations, and improper blending procedures. However, during the 1-year full-scale validation phase of the program when the amount of AMK fuel prepared exceeded the total amount for the preceding years there were no in-line blending problems (34). The AMK fuel was consistently produced within specifications and with steadily improving equilibration times and flammability resistance.

## AMK COMPATIBILITY

Investigations of AMK compatibility with individual engine components, airframe fuel systems and components, tank sealants and coatings, bladder cell material, and elastomers have been conducted both in the U.S. and U.K. since 1979. In England, the major contributors have been RAE, Plessey, Lucas, and Rolls Royce. In the U.S., the major work was done by the FAA Technical Center and Center contractors, namely, PWA, General Electric (GE), Douglas, Boeing, SWRI, and JPL.

The FAA has demonstrated that jet engines can operate on undegraded FM-9 AMK fuel (35). However, studies here and in England clearly show that the FM-9 polymer must be highly degraded and the AMK restored to near Jet A properties, if modern engines are to operate efficiently on AMK. JPL investigated the relationship among the level of degradation, fuel atomization, combustion efficiency, and stability (36). JPL, in rig tests with a standard combustor and fuel nozzle, found that combustion efficiencies decreased and hydrocarbon and carbon monoxide emissions increased with increasing filter ratios and droplet sizes. Earlier work by PWA and Lucas Aerospace showed similar trends (13,37).

Various methods for degrading AMK have been investigated and all result in a net energy loss to the engine cycle. In future designs, the degrader would be expected to become an integral part of the engine fuel pump and control system to keep weight and energy requirements to a minimum.

In work for the RAE, Plessey Aerospace Limited developed a combined pump-degrader (38,39). The high power requirements of the unit indicated that a systems approach should be used to take advantage of the degradation provided by other fuel system components.

JPL, PWA, and Plessey investigated non-mechanical methods for degrading AMK, including ultraviolet light, catalysis, ultrasonics, lasers, cavitation, and centrifuges. Plessey concluded that the non-mechanical methods were ineffective, too slow, or not suitable for aircraft applications (38). PWA has used commercial cavitation devices successfully to degrade AMK (14), but size and power requirements preclude the use of these units in aircraft. However, PWA and United Technologies Research Center believe that AMK can be adequately degraded with a multistaged cavitating venturi based on results of tests with a single-stage unit (40).

SWRI developed hydro-mechanical degraders that use variable flow pumps to force the AMK fuel through flow restrictors at high pressure (11,41). SWRI evaluated the filtration performance of degraded AMK by locating JT8D and CF6 engine filters immediately downstream of the high pressure degrader. The results indicated that degraded AMK flows through the filters at pressures close to those required for Jet A. The degrader pressure had to be increased to produce satisfactory filter performance when the fuel temperature was below 0 degrees Celsius.

In an AMK fuel system study (42) of in-line blending, degradation, filtration, and combustion, JPL used a high pressure degrader. JPL demonstrated that fresh, in-line blended AMK fuel at 20 degrees Celsius can be degraded and

filtered within 20 minutes after blending. The degraded AMK failed the filtration test, however, when the fuel temperature was lowered to -20 degrees Celsius. Fuel heating or a higher degrader pressure would be required to filter low temperature fuel with this type of degrader.

General Electric developed a flight degrader for the FAA based on a high speed centrifugal fuel pump (43). Bench tests of the unit produced high fuel degradation levels over a full range of flow conditions. The specific fuel consumption penalty for engine gearbox power extraction for such a pump degraded was estimated by GE to be relatively low. This concept was further developed by GE and was used on both the CV880 flight test vehicle and the B720 Controlled Impact Demonstration (CID) aircraft.

Lockheed-Georgia Company used a full-scale, C141 aircraft fuel system simulator to evaluate system and component performance with FM-9 AMK which was batch-blended without carrier fluid (44). Results of the Lockheed tests showed that AMK was compatible with capacitance gauges. AMK did reduce the performance of fuel tank boost and ejector pumps. Although the engine fuel pump operated satisfactorily without a degrader, the fine engine filter was bypassed during simulated takeoff and cruise fuel flow rates. Lockheed tests also showed increases in fuel transfer and fuel level control valve closing times with AMK.

AMK fuel system performance was also successfully demonstrated in the KC/DC-10 ground simulator at Douglas Aircraft (45) and the B747/B767 ground simulators at Boeing (30). The KC/DC-10 tests were all conducted at sea level ambient temperature. These tests included full-scale fill and vent system flow and functional tests, engine feed system flight cycle simulations, and aerial refueling system flow and functional tests.

The Boeing program emphasized fuel system component operation at simulated environmental extremes. The AMK fuel was exposed to severe low temperature flight profiles with slosh and vibration, repeated thermal cycling, a "worst-case" vent/ullage water vapor environment, suction feed at cold temperatures and altitude extremes, and boost pump delivery endurance at cold fuel extremes.

Overall results of the Douglas and Boeing programs demonstrated that the FM-9 AMK fuel retained the mist suppression properties when exposed to airframe fuel system operation at flight envelope and environmental extremes. The AMK fuel reduced the performance of some fuel subsystems (e.g., jet pump transfer, gravity transfer, suction feed, and boost pump feed) below normally accepted levels, at certain conditions. However, these deficiencies could be remedied by either fuel management procedural or minor hardware changes. The results of these tests also demonstrated the resistance of FM-9 AMK to unwanted degradation in airframe fuel systems.

The Boeing evaluation of AMK also showed that the amount of water ingested into a fuel tank during "worst-case" simulated flight conditions was too small to affect the fuel. If water vapor is added to a tank containing FM-9 AMK fuel, a true solution of water in AMK occurs (33). As more water is added, a

micro-emulsion can form; and, finally, if the water level is sufficient to form coarse droplets, a white precipitate can develop. JPL found that the uptake of water in AMK can be as high as 1,300 ppm compared with Jet A which saturates at less than 100 ppm (32). More than 250 to 300 ppm water in AMK under static conditions is necessary to initiate the formation of an insoluble second phase. However, based on the Boeing tests, environmentally-introduced water through condensation and coalescing is a gradual process and the levels remained below those required to produce this second phase during four consecutive flight cycles under worst-case conditions.

Compatibility tests on tank sealants and coatings, fuel tank bladder cell material, and fuel system elastomers by Product Research and Chemical Corporation, Goodyear Aerospace Corporation, and PWA indicated that the reactions of these materials with AMK were within specifications (46,47,14).

PWA detected sodium levels in samples of AMK fuel which could appreciably accelerate hot section corrosion in turbine engines. Subsequently, ICI developed processing changes and has produced small quantities of sodium-free FM-9 (48).

As part of an overall evaluation of AMK performance and safety, the FAA Technical Center operated jet engines on undegraded FM-9 AMK (49,50,51,39). The engines were started on Jet A fuel and then operated on undegraded AMK without any operational problems. The engine's thermodynamic performance, efficiencies, and fuel consumption all deteriorated due apparently to the poor atomization of the undegraded fuel.

The FAA engine tests on undegraded fuel included an investigation with a PWA JT3C-6 engine in a standard configuration and with the fuel system modified to correspond to the JT3C-7 engine installed on the CID B720 aircraft (35). The engine was operated on undegraded AMK for over 4 hours during 3 test runs. Although differential pressures across fuel filters and nozzles increased, there were no operational problems, and pre-test and post-test calibrations on Jet A showed no significant differences in engine operating characteristics.

FAA JT3C engine tests on various levels of degraded AMK also showed that there were no measurable performance difference between Jet A and AMK operation. At low degrader power levels, shear induced soluble gel was formed on the downstream side of fine mesh fuel filters. During the initial 15 hours of AMK fuel operation with the JT3C engine, insoluble gels also formed on the engine fuel filters during several test runs. The soft, soluble gel caused a step change in the differential pressure across the filter while the insoluble, hard gel produced a gradual rise in the differential pressure with time. This rise in differential pressure continued until the filter started bypassing fuel or until the engine was shutdown. The last 18 hours of AMK engine tests were completed without the insoluble gel problem and with the soluble gel being detected only during test runs with the engine operating on undegraded AMK. These final test runs were made under conditions nearly identical to the conditions which resulted in the hard gel during the initial runs. As discussed in the Flight Test Section, this problem has not been fully explained and needs to be investigated further.

PWA conducted a 2-year technical assessment of AMK on the performance of fuel system components and combustors of a low bypass ratio turbofan engine (14). Lucas Aerospace Limited evaluated the performance of an annular combustor of a high bypass ratio, turbofan engine and fuel injectors in a similar study (37,52).

In general, both programs showed the sensitivity of combustion efficiencies and carbon monoxide and unburned hydrocarbon emissions to the level of AMK degradation. While neither program uncovered any unsolvable problems, both companies stressed the importance of endurance testing in order to determine long-term effects on critical engine components and performance.

#### FLIGHT TESTS

The first aircraft to fly with an engine operating on FM-9 AMK was the Convair 880 under an FAA/GE contract. The GE centrifugal degrader was installed on the number three engine, which was fueled with AMK from the No. 3 wing tank. The aircraft's other three engines operated on Jet A. The No. 2 engine was instrumented to serve as the reference engine for the No. 3 engine. Due to time constraints, the flight degrader development by GE utilized existing flightworthy components. An F101 engine centrifugal pump and a C-5A aircraft auxiliary power air turbine motor were selected as the primary hardware for the bleed air driven degrader. A throttling valve was used to reduce the fuel pressure to levels acceptable for the main engine fuel pump. Excess fuel was recirculated to the degrader inlet through a heat exchanger.

The same basic air turbine/degrader system was installed on each of the four engines of the B720 CID aircraft. The major installation differences between the two aircraft were the locations of the air-fuel heat exchanger (CV880 - ECS bay and B720 - underwing pod) and the degrader pump-drive assemblies (CV880 - bottom of engine and B720 - top of engine). The hardware selection and arrangements were driven by expediency and not by considered design. The degrader-pressure regulating function would be expected to be incorporated within the main engine fuel pump in production systems. This would reduce the system weight and power requirements and would eliminate additional fuel lines around the engine.

Except for additional instrumentation, no modifications were made to the standard engine fuel systems downstream of the degraders in both the CV880 and B720 installations.

The flight test objectives of the CV880 program were to determine, on a representative commercial aircraft, the effect of AMK on the aircraft fuel system performance, the effect of the fuel systems and flight environment on the quality of the AMK fuel, and the installation and operational requirements for a prototype flight degrader.

The CV880, with four GE CJ805 engines, was chosen as a representative commercial aircraft. Although this aircraft is no longer used by U.S.

commercial carriers, the airframe and engine fuel systems are representative of modern aircraft systems.

The flight test program was successful, providing the required technical data and the degrader development necessary for the four engine degrader installation and operation on the CID B720 aircraft (34,53). The on-the-wing engine ground runs and 14 test flights under the GE CV880 program accomplished the following:

1. A total of 45 hours of degrader operation on AMK fuel, including 30 hours of aircraft flight tests.
2. Flights completed with no major degrader system hardware failures or design problems.
3. Ground and flight tests operationally acceptable over a range of fuel tank temperatures from 0 to 90 degrees Fahrenheit.
4. Ground starting acceptable at fuel temperature from 50 to 90 degrees Fahrenheit.
5. Altitude relight capabilities at 10,000 to 30,000 feet and 0.5 to 0.6 Mach numbers--the same as Jet A fuel baselines.
6. Engine acceleration/deceleration at 10,000 to 40,000 feet altitudes--the same as Jet A fuel baselines.
7. Analysis of AMK fuel samples taken from the No. 3 main tank substantiated that the fuel maintained the required mist suppression qualities throughout the flight test environment.
8. Analysis of AMK fuel samples taken from the degrader discharge line during ground tests and following flight tests showed the AMK fuel to be highly degraded.

A demonstration of the degradability of in-line, freshly-blended AMK was buildup. Also during the period of gel formation, the in-line blended AMK fuel exhibited marginal equilibration times and equilibrated properties. The AMK fuel characteristics during the final 26 hours of tests were consistently of high quality.

During the CV880 tests, a pressure spike across a fine filter was detected each time the engine was switched from Jet A fuel to AMK fuel. The differential pressure returned to a normal level after operating on AMK for a short period of time. A test was interrupted during the transition from Jet A to AMK, and the filter was removed and inspected. A sticky film, which was soluble in AMK, was found on the filter. Use of glycol in the Jet A prevented this pressure spike and the film buildup on the filter. This reaction was duplicated in the laboratory using the filter ratio device. The laboratory tests showed that the filter resistance decreased with time after mixing Jet A and AMK fuels. More needs to be learned about this potential problem.

During a CV880 flight, the degrader was intentionally shut down while operating on AMK. The engine continued operating normally on undegraded AMK, although a step increase in the differential pressures across the engine fuel filters was noted. These pressure rises returned to normal levels after the degrader was restarted with the engine continuing to operate on AMK. Work by SWRI and the FAA had shown that once a critical velocity through a filter is exceeded, a

shear induced soluble gel forms on the downstream side of the filter. This critical velocity increases with level of degradation and filter size. When the level of degradation is increased or the flow rate through the filter is decreased, the gel will dissolve, and the filter will flow unrestricted.

Reports on the results of the GE flight degrader development and AMK flight test investigation are scheduled to be published by the end of 1985 (53).

A phased flight plan was conducted during the manned B720 flights to establish confidence in the reliability and performance for four engines operation during the unmanned CID flight (34). Each degrader engine system was first qualified on Jet A before each system was ground and flight tested on AMK. The center wing tank, override boost pump, and crossfeed manifold system were dedicated and used exclusively to deliver AMK to each of the degrader/ engines. During the course of the flight tests, only minor problems were identified in the areas of mechanical installation, instrumentation, degrader control, and operation procedures.

A degrader inadvertently shutdown while operating on AMK during a go-around climbout. The engine continued operating normally on AMK for about one minute, after which the engine was switched to Jet A. The post-flight debriefing of the crew reported no operational difference between AMK, undegraded AMK, and Jet A operations. The flight engineer's degrader control panel and the ground control room readouts were the only indications of degrader shutdown. Instrumentation showed the characteristic pressure rise across fuel filters, which returned to normal levels immediately after the switchover to Jet A fuel. Post-flight inspection of these filters showed evidence of residual, shear-induced gel.

The installed steady state engine performance with AMK, as compared to Jet A, showed no significant changes in exhaust gas temperature and fuel flow rates increased between 1/2 and 1-1/2 percent. The increase in fuel flow was primarily due to the bleed air used to drive the oversized degrader units. The AMK degradation levels of engine boost pump inlet samples taken during ground runs, ranged from moderately high levels at idle power to very high levels at cruise settings.

AMK fuel samples taken from the wing tank after the initial fill and prior to and after two manned flights provided data on the AMK quality in an aircraft for a period of 20 days. Results show that normal ramp and flight exposures do not significantly affect the quality of the AMK fuel.

The B720 degrader systems accumulated a total of 27 hours on Jet A and 11 hours on AMK fuel by the completion of the manned, ground and flight qualification tests.

#### IMPACT DEMONSTRATION

The objectives of the AMK program B720 impact demonstration were to operate full-scale transport fuel and propulsion systems totally on AMK fuel and to

demonstrate that the fuel can prevent ignition of an airborne fuel mist or suppress the propagation and growth of any resulting flame. The aircraft was to carry a full load of high quality in-line blended AMK while remotely-piloted to a designated impact point. The aircraft was to impact at a speed of 155 knots and immediately strike ground obstructions designed to produce multiple wing tank ruptures. The fuel from the ruptured tanks was to be exposed to ignition sources during the subsequent slide out. The planned ignition sources included engines separated from the wing, the aircraft electrical system, an open flame located to simulate ignition by an aft-mounted engine, impact site gravel, and operating approach lights.

Approximately 11,400 gallons of AMK was in-line blended directly into the five main and two reserve tanks of the B720 aircraft, starting about 39 hours prior to brake release. The blending operation was performed by FAA personnel on the flight line of the NASA Ames Dryden Flight Research Facility. Analysis of fuel samples taken from each tank showed that high quality AMK developed within the first hour after completing the blend (34). The first engine was started on AMK fuel approximately one hour prior to brake release. All four degraders responded normally to the takeoff fuel flow demands of the remotely-located NASA crew through rotation and climbout. The degraders continued to respond normally to the required fuel flow excursions throughout the flight.

The B720 was flown remotely from the ground using the onboard autopilot as the primary control. Extensive flight tests were performed to practice the impact scenario. The CID mission proved to be a high workload task for the pilot due to the requirement of integrating information from many sources, in an attempt to meet the tight impact constraints (54). As a result of the high workload, not all of the impact parameters were met, and the impact deviated from the planned AMK program goals. Along with the 150-knot longitudinal speed, the planned scenario specified a vertical descent rate of 17 feet per second at ground impact. A nose-up attitude of one degree was specified to achieve the planned fuselage impact location, just aft of the wing box. In addition, the yaw and roll limitations at impact were to be less than two degrees in order to assure a symmetrical impulse to the fuselage.

The attitude, roll, and yaw limitations were greatly exceeded. The aircraft first struck the ground at 152 knots with the left outboard engine, 410 feet short of the planned impact point. The aircraft was in a left yaw of 13 degrees and rolled left 13 degrees. The attitude of the fuselage at impact was two degrees nose down.

The No. 1 and No. 2 engines spooled down to cutoff immediately after the left wing and fuselage contacted the ground, and both engines separated at the pylon during the next two seconds, prior to reaching the wing opener obstructions. By the time the aircraft reached the wing openers, it had slid 500 feet, the yaw angle increased to 38 degrees left, and the speed had decayed to 122 knots. The initial wing opener contact occurred with the leading edge of the right wing almost perpendicular to the center line of the impact zone. Both right wing engines were still operating at the initial impact with the openers. The right inboard engine (No. 3) was first struck by the openers. The wing obstruction entered the side of nacelle and continued through the engine,

stopping the compressor rotation within one revolution. As the opener buried itself in the engine, the supporting structure broke loose from the anchors, and the opener assembly rotated upward, cutting into the underside of the wing. Simultaneously, a second wing opener tore through the underside of the wing just inboard of the damaged No. 3 engine, causing sufficient damage to separate the wing. The right wing fractured just inside the inboard engine and rotated upward, releasing most of the fuel (2,150 gallons) from the inboard right main tank.

Because of the yaw, three wing openers on the right side severely damaged the fuselage and opened holes through which fuel from the severed wing entered the cargo area. Also, at fuselage impact, the right forward cargo door opened, allowing additional fuel to enter the cargo area.

Ignition occurred on the inboard side of the No. 3 engine 1.2 seconds after initial impact with the wing opener. The initial ignition was unlike that typically produced by AMK and probably involved misted lubricating oil, degraded AMK, and hydraulic fluid from the destroyed engine. Considerable turbulence was being generated because of the sideward slide of the fuselage and the release of large amounts of fuel from the severed wing, which was rotating in front of the fuselage. The aircraft yaw produced an area of intense recirculation in the immediate vicinity of the failed engine. AMK fuel spilled into this region and was repeatedly sheared and exposed to heat from the burning combustible fluids and hot engine surfaces. The shear and extended residence time caused the AMK fuel to vaporize and burn.

The initial impression prior to viewing the extensive photographic coverage was that the AMK fuel had failed to suppress the mist fireball and had, in fact, initiated a large pool fire. Careful review of the film revealed that the fire was not an ignition of misted fuel and that when the aircraft came to rest, there was no large pool fire. The film shows that the airborne fire engulfing the fuselage went out within eight seconds of the initial ignition, at which time the fuselage had suffered only minor fire damage. The fire that eventually destroyed the aircraft was caused by burning fuel that entered openings in the lower fuselage.

The mechanism of AMK fuel burning in the CID was the result of the aircraft's unique yaw during impact and slide out. Without the yaw, any flame from the wing area would have been blown aft without impinging on the fuselage. The No. 3 engine would have been expected to separate from the wing on impact with a wing opener or the ground, and damage to the engine would have been significantly reduced.

Liquid and burning fuel entered the lower fuselage compartments as a result of the high yaw angle and eventually destroyed the entire cabin. Therefore, with low yaw conditions, occupant egress and overall survivability would have been significantly enhanced.

Therefore, if the CID had gone as planned, with the aircraft impacting the wing openers at little or no yaw, the results would have been significantly

different. Any fire development would have been limited to areas aft of the aircraft, attached to separated engines or slow developing ground fires.

However, if Jet A fuel had been onboard the aircraft instead of AMK, the degree of yaw would not have been significant. Even a minor intermittent ignition source would have led to a devastating fire. The airborne fire would have been characterized by much higher flame growth and heat transfer rates, propagation to fuel release locations, and attachment to the aircraft after slide out.

#### POST-CID STUDIES

Work undertaken since the CID has been designed to provide data and explanations in two areas. First, what mechanism produced the large ignition and continued burning of the AMK? Second, why did the apparently severe flames produce minimal fuselage damage?

To gather data on why such a fire occurred, FAA contractors and the FAA Technical Center conducted a series of experiments that were designed to duplicate the events of the CID.

Review of the CID data indicated that fuel was released from the wing ruptures at rates estimated to be 300 to 400 gallons per second. Prior AMK work had examined release rates in the 20 to 100 gallon per second range. The initial ignition of the fuel in the CID appears to have been associated with a release of high energy flame or gas from the ruptured engine. A burst of flame from the compressor acceleration bleed port on the inboard side of the engine or the frictional energy of the cutter slicing through the metal of the nacelle and engine could have caused ignition.

The Technical Center has systematically examined these aspects using the wing-fuel spillage facility. A fully cowled, 3,000-pound thrust class turbojet engine was mounted under the airfoil section at an angle of 38 degrees to the airflow. The engine installation was positioned such that the fuel release (simulating a ruptured wing tank) was in the same relative position as in the actual CID. Fuel was released at a rate of 300 to 400 gallons per second into the airflow.

During the release, with the engine at 90 percent power and the airflow set at 125 knots, fuel inadvertently entered the inlet of the engine causing a surge. The surge, which in this test served to ignite the fuel, was not a factor in the CID. A continuous fire immediately established itself in the sheltered path downstream of the engine. Fuel that continued to pour out showed the typical coarse spray characteristic of AMK. No propagation upstream of the engine or to the release port occurred.

This sequence illustrated what probably occurred in the CID after the initial ignition. The turbulence and recirculation in the area sheltered by the engine and pylon provided sufficient shear force to break up the AMK, and the recirculation provided sufficient residence time for the fuel to vaporize and burn after being exposed to a severe engine surge.

During subsequent tests, with the engine oriented in-line with the airflow (as was intended in CID), a phenomenon not encountered in all prior AMK work occurred. The AMK entrained by the engine exhaust produced an extremely fine fuel mist. The high velocity exhaust was providing severe shearing forces that degraded the AMK. This did not occur at CID because the engine exposed to fuel from the ruptured tank stopped rotating within one revolution. The exhaust of the turbine engine, which was about 650 degrees Fahrenheit and 300 knots, did not ignite the AMK. Use of a spark gap ignitor of up to 2 joules in the plane of the exhaust discharge was also insufficient to cause ignition. However, a small, open flame at the same location was sufficient to ignite the jet fuel mist in the exhaust.

Regarding the relatively good condition of the B720 fuselage when the initial flame lifted, there are some preliminary indications that slower propagation rates of AMK and coarser AMK liquid breakup result in a cooler flame and slower transfer of heat to the impinged surfaces.

Additional work is needed on AMK ignition to define more precisely the ignition envelope and burning characteristics of the fuel under such unique conditions. This includes studies investigating the impingement characteristics of modified fuels on bluff bodies at different surface temperatures and the potential for ignition and sustained combustion in recirculation zones.

Additional work is also needed on engine exhaust entrainment of fuel to establish the ignition boundaries of AMK as a function of the type, size, intensity, and location of the ignition source.

The results of these studies should define more accurately AMK's envelope of effectiveness and any aircraft modifications required to enhance the post-crash fire protection provided by AMK fuel. The results from these investigations should also help determine more precisely the performance requirements for antimisting fuels.

While no experiment as complex as the CID can be expected to perform exactly as planned, the CID was unique. A detailed review of the National Transportation Safety Board data on over 700 accidents, involving U.S. turbine-powered aircraft from 1964 through 1983, yielded no impact-survivable accident that had all the critical elements of the CID, namely: post-crash fire; major wing engine damage without separation; large fuel release at the damaged engine; yaw greater than 30 degrees; and fuel ignition between 100 and 150 knots (55).

Two accidents showed characteristics somewhat similar to the CID. One of these accidents involved an Overseas National Airways DC-10 at JFK International Airport on November 12, 1975. While it had many of the CID elements, it did not have the critical high yaw angle that occurred in the CID. In the other accident (American Airlines B707, Denver, Colorado, March 5, 1973), the damaged wing-mounted engine separated at impact and the fuel tanks remained intact.

Based on the available information, it is estimated that AMK could have provided protection in at least 80 percent (36 out of 45) of the impact-survivable accidents involving post-crash fires during this 20-year

period. In the other accidents, AMK fuel would have been of limited value because the fires either were not due to fuel, the fuel release occurred at the ignition source, or the fire started after the aircraft came to rest. Of the 36 accidents where AMK was expected to provide protection, 13 of the most severe were considered to be like the CID as planned. Twenty-seven of 36 accidents where AMK protection was not expected were not impact-survivable. In about 21 percent (19 out of 91) of the post-crash fire accident documentation provided insufficient data for classification.

As a result of this analysis, and consistent with earlier recommendations of the SAFER Committee (2), we believe that present accident documentation could be improved to help assess the role of fuel and ignition sources in post-crash fire development. Some of the specific shortcomings of accident data include little detail on location and size of the fuel release and source of ignition, and on the sequence of events during and immediately after slide out.

#### STATUS OF AMK TECHNOLOGY

Laboratory tests have been developed which characterize the antimisting, filtration, and flammability properties and degradation level of antimisting kerosene fuel. Important heat transfer, friction, and viscoelastic rheological properties of the fuel have been explained and quantified.

Higher airport fuel handling standards will be required to prevent accidental introduction of bulk water which would cause severe precipitation problems in fuel systems with FM-9 AMK fuel. Environmentally introduced water through condensation and coalescing is not considered to be a problem since normal introduction of water during operational use is a gradual process. Results to date indicate that a very high degree of protection against impact-survivable, post-crash fuel mist fires would be provided by AMK fuel. This protection would be available a few minutes after refueling for a range of aircraft impact speeds and fuel temperatures covering most takeoff conditions encountered in commercial air transportation. The degree of protection at the end of a typical flight cycle would be essentially the same as on the takeoff, provided that certain aircraft fuel systems are reworked to prevent unintentional degradation in the fuel tank system.

The lack of long-duration tests of aircraft fuel systems leaves some questions unanswered on the changes necessary for civil aircraft operation on AMK fuel. However, the following components are expected to require modifications or replacement on some aircraft: tank jet pumps used for critical fuel transfer; tank fill valves; engine system filters; engine boost pumps; and fuel flowmeters. The engine fuel control system, fuel nozzles, and combustors appear to function effectively, provided that the AMK fuel is highly-degraded. One of the critical demands for highly degraded fuel is imposed by the heat exchangers. Component modification or procedural revisions to solve fuel system hardware problems associated with AMK fuel, are not considered technically insurmountable.

It appears to be feasible, with improved airport fuel handling procedures, to blend the AMK additives with Jet A fuel at the aircraft fueling point and to degrade the fuel efficiently within a reasonable time period. Single-stage blending appears to be practical for day-to-day commercial operation with the current FM-9 additive. Incorporation of in-line blending procedures and techniques into production blenders should present no problems.

Engine performance with degraded AMK appears satisfactory, even in critical areas such as altitude relight. Degradation can be achieved without excessive power by making use of the degradation occurring in system components upstream of the engine, and then using a modified boost pump to complete this process. Development of the degrader system is not as far along as in-line blending. However, with the basic principles demonstrated in prototype units, practical degrader designs should be developed with few problems.

A computer model has been developed (4,56,57) for determining the cost of introducing and using the fuel and for weighing these costs against potential benefits (lives saved, equipment salvaged, and possible reduction of insurance costs). Such information has been and should continue to be updated. The extra cost resulting from the FM-9 additive and aircraft and airport modifications, at the present is estimated to be 5 percent (maximum) of the price of the fuel used to operate the aircraft or a 2 to 3 percent increase in the cost of a ticket.

The actual CID experiment encountered conditions beyond the design goals set for AMK fuel. Although extensive pre-CID testing had provided strong evidence that the AMK fuel used in the CID had properties that would have precluded fireball development, the unique flow conditions and geometry that occurred exceeded the design capabilities of the fuel.

The exhaust entrainment of spilled fuel may prove to be a problem. Entrainment is likely to degrade the antimisting characteristic of the fuel to the degree that an open flame could cause the degraded AMK to burn severely. However, without yaw, any burning of fuel entrained in the exhaust would be expected to take place behind the aircraft, and the fuselage would not become involved.

Similarly, any fire development from fuel entrained in the exhaust of aft-mounted engines would be well behind the aircraft. With adequate time for the full development of the antimisting properties of the fuel from ruptured wings, forward propagation is highly unlikely.

Based on an analysis of past accidents, the CID was an unique event. The pilot was attempting to impact an extremely small target area and achieve this with a marginal remote control system. This combination caused a loss of directional control. The unusual geometry and flow patterns of the CID are unlikely to occur as indicated by past accident documentation.

Investigations now underway, or proposed as future work, are aimed at defining more precisely ignition and burning characteristics of the AMK fuel and minimizing the possibility of ignition. Until recently, most AMK development concentrated on the existing FM-9 antimisting additive for proof of concept.

The manufacturer reports that there are more advanced derivatives under development. Manufacturers of other fuel modifiers are being encouraged to become involved in this effort. Renewed interest on the part of industry to provide improved antimisting fuel additives as well as alternative approaches is also encouraging (58).

There are concepts for dealing with problems caused by intense ignition sources and recirculation. These include the use of fast-acting fuel shutoff valves, boost pump shutdown devices, tank compartmentization, tank baffling, fuel isolation, and engine shutdown.

Some technical problems uncovered during the pre-CID research still require further effort before the fuel can be considered operationally acceptable. The occurrence of insoluble gel in FM-9 AMK during some early flight test and engine test cell work has not been fully explained. The most probable cause of this gel is a contamination that had accumulated in the system prior to the introduction of AMK fuel. Also not yet fully explained is the gel formed when normal kerosene fuel is added to a system containing residual AMK. Finally, more data are needed on the effects of prolonged use of AMK on fuel and propulsion systems.

Future safety fuels, when combined with a system approach, should prove to be effective in reducing the post-crash fire hazard in commercial air transportation and should be a part of our future aviation safety technology.

## REFERENCES

1. Klueg, E. P., Imbrogno, S. L., and Fenton, B. C., Aircraft Fuel Safety Research with Antimisting Fuels--A Status Report, DOT/FAA/CT-82/95, June 1982.
2. Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee Final Report, Volume 1, FAA-ASF-80-4, July 1980.
3. Engineering and Development Program Plan Antimisting Fuel, FAA-ED-18-4, September 1980.
4. Economic Aspects of Conversion to Antimisting Kerosene, The Aerospace Corporation, Report N. ATR-81(6862)-IND, November 1981.
5. Safety Fuels, British Civil Aviation Authority, Research Paper No. CARDPB/P(76)102, July 1976.
6. Azad, B. and Poston, P., U.S. Commercial Fleet Usage of Antimisting Fuels: Survey and Analysis, DOT/FAA/CT-82/59, September 1983.
7. Mannheimer, R. J., Rheology Study of Antimisting Fuels, FAA-RD-77-10, January 1977.
8. Peng, S. T. J. and Landel, R. F., Rheological Behavior of Progressively Shear-Thickening Solutions. Journal of Applied Physics, V52, N10, P5988-5993, 1981.
9. Ferrara, A. and Hoover, R., Practical Real-Time Quality Control of Antimisting Kerosene, DOT/FAA/CT-85/1.
10. Mannheimer, R. J., Real-Time Quality Control of Antimisting Kerosene, DOT/FAA/CT-85/5, To Be Published.
11. Mannheimer, R. J., Degradation and Characterization of Antimisting Kerosene (AMK), DOT/FAA/CT-82/93, December 1982.
12. Derrickson, J. L., A Procedure for Analyzing Antimisting Kerosene Using Gel Permeation Chromatography, DOT/FAA/CT-TN84/30, August 1984.
13. Fiorentino, A., DeSaro, R., and Franz, T., An Assessment of the Use of Antimisting Fuel in Turbofan Engines, FAA-CT-81-58, June 1981.
14. Fiorentino, A. J. and Planell, J. R., An Assessment of the Use of Antimisting Fuel in Turbofan Engines, NASA CR-168081, October 1983.
15. Real-Time Quality Control of AMK, Monthly Progress Report, Southwest Research Institute, U.S. Army Fuels and Lubricants Research Laboratory, Contract No. DAAK70-82-C-0001, (FAA), June 1984.
16. Wat, J. and Sarohia, V., Frictional Characteristics and Heat Transfer of Antimisting Fuel in Tubes, DOT/FAA/CT-82/20, August 1982.

17. Salmon, R. F., Wing Spillage Tests Using Antimisting Fuel, FAA/CT-81/11, February 1981.
18. Webster, H., AMK Flammability Tests Using the Wing Spillage Facility, DOT/FAA/CT-85/13, To Be Published.
19. Schaible, J. J., Large-Scale Aircraft Crash Tests of Antimisting Kerosene, Naval Air Engineering Center Test Department, NAEC-TR190, May 21, 1982.
20. Schaible, J. J., Crash Test of an RB-66 Aircraft Fueled with Antimisting Kerosene FM-9, Naval Air Engineering Center Test Department NAEC-TR198, September 9, 1983.
21. Mahood, L. and Talley, R. L., Correlation of Flammability Test Data on Antimisting Fuels, DOT/FAA/CT-82/29, December 1982.
22. Ferrara, A. M. and Cavage, W. C., Flammability Comparison Test Apparatus Operator's Manual, DOT/FAA/CT-TN84/50, March 1985.
23. Parikh, P. Fleeter, R., and Sarohia, V., Antimisting Fuel Breakup and Flammability, DOT/FAA/CT-82/149, December 1983.
24. Status of U.S./U.K. Antimisting Fuel Program, The Introduction of Antimisting Additive into Aviation Kerosene, The 8th AMK Joint U.S./U.K. Technical Group Meeting, September 1980.
25. Study of the Facilities Required for the Bulk Handling, Storage, and Delivery into Aircraft of a Two-Stage Blended FM-9 Fuel, Prepared by Shell International Trading Company Aviation Field Services, for the Royal Aircraft Establishment Materials Department, April 1982.
26. Aircraft Research and Technology for Antimisting Kerosene, DOT/FAA/CT-81/181, February 1981.
27. Yavrouian, A. H., Ernest, J., and Sarohia, V., Antimisting Kerosene: Base Fuel Effects: Blending and Quality Control Techniques, DOT/FAA/CT-83/36, January 1984.
28. Parikh, P., Yavrouian, A., and Sarohia, V., Antimisting Kerosene: Development of a Continuous 10 GPM Inline Blender, DOT/FAA/CT-85/12, To Be Published.
29. Byrnes, H. S., and Webster, H., Development of a Large-Scale Antimisting Kerosene Blender, DOT/FAA/CT-85/24, To Be Published.
30. McConnell, P. M., Tolle, F. F., and Mehta, H. K., Aircraft Wing Fuel Tank Environmental Simulator Tests for Evaluation of Antimisting Fuels, DOT/FAA/CT-84/15, September 1984.
31. Full-Scale Transport Controlled Impact Demonstration Program, DOT/FAA/CT-82/151, January 1984.

32. Yavrouian, A. H., Sarboluki, M., and Sarohia, V., Influence of Liquid Water and Water Vapor on Antimisting Kerosene (AMK), DOT/FAA/CT-82/18, February 1983.
33. Water Compatibility With AMK-FM-9, Detailed minutes of meeting which was held November 17, 1981, at the Jet Propulsion Laboratory.
34. Fenton, B. C., Antimisting Fuel Technology Application in Full-Scale Transport Aircraft, The 16th International Seminar of the International Society of Air Safety Investigators, September 1985.
35. Rust, T., Compatibility Study of Antimisting Kerosene with the JT3C Engine Fuel System, FAA Report, To Be Published.
36. Fleeter, R., Parikh, P., and Sarohia, V., Atomization and Combustion Performance of Antimisting Kerosene and Jet Fuel, DOT/FAA/CT-82/150, December 1983.
37. An Assessment of the Performance of an RB211 Combustor Using Antimisting Kerosene (FM-9), Lucas Aerospace Fabrications Division Report No. B 49 556, May 1982.
38. Jones, P. W., Antimisting Kerosene Investigation: Development of a Pump and Degradar, Plessey Aerospace Limited Technical Report No. 16/83/1828A, March 1983.
39. Jones, P. W., Antimisting Kerosene Investigation: Improving Jet Pump Efficiencies, Plessey Aerospace Limited Technical Report No. 16/83/1833A, March 1983.
40. Szetela, E. J., and TeVelde, J. A., Vortex Venturi Antimisting Fuel Reverter Performance, United Technologies Research Center Report, UTRC81-55, October 1981.
41. Mannheimer, R. J., Feasibility of a Full-Scale Degradar for Antimisting Kerosene, Journal of Aircraft, p. 335, May 1984.
42. Antimisting Kerosene (AMK) Research Phase IV Semi-Annual Program Review, Jet Propulsion Laboratory, May 21-23, 1984.
43. Coffinberry, G. A., Antimisting Fuel Degradar Investigation, DOT/FAA/CT-82/72, June 1982.
44. Pardue, R. E., Aircraft Fuel System Simulator Tests With Antimisting Kerosene (Jet A Fuel With FM-9 Additive), FAA-RD-79-52, May 1979.
45. Ching, F. Y., and Peacock, A. T., Compatibility Study of Antimisting Kerosene and the DC-10/KC-10 Fuel System, DOT/FAA/CT-82/116, March 1983.
46. Singh, H., Compatibility Tests on PRC Aircraft Fuel Tank Sealants and Coatings Using Antimisting Fuel Containing FM-9, Products Research and Chemical Corporation, March 25, 1982 Letter.

47. Aircraft Research and Technology for Antimisting Fuel Bimonthly Bulletin, FAA Technical Center, Engine/Fuel Safety Branch, October-November 1982.
48. Fuel: Additive, Blending, and Assessment, Detailed Minutes of Twelfth Meeting of the U.S./U.K. Technical Group on Antimisting Kerosene, May 1985.
49. AMK Degradation, FAA Technical Center Position Paper, November 25, 1983.
50. Engine Operation on Undegraded Antimisting Fuel, FAA Technical Center Position Paper, May 29, 1984.
51. Requirement for Operation of a JT3C Engine on Undegraded AMK Fuel, Letter from FAA Technical Center to NASA Ames Research Center, July 3, 1984.
52. Droplet Size Determinations on Three Types of Fuel Injectors Using Aviation Kerosene and Three Samples of an Antimisting Kerosene Degraded to Different Levels, Lucas Aerospace Fabrications Division Report No. B 49 530, June 1981.
53. Antimisting Kerosene Ground, Flight, and System Testing, General Electric Aircraft Engine Business Group, Contract DTFA03-83-C-00018 Reports, To Be Published.
54. Kempel, R. W., and Horton, T. W., Flight Tests Experience and Controlled Impact of a Large Four-Engine Remotely Piloted Vehicle, Presented at the 16th Annual Society of Flight Test Engineers Symposium, July 29 to August 2, 1985.
55. Ferrara, A. M., Howard, F. B., and Klueg, E. P., An Analysis of Antimisting Fuel Effectiveness on Post-Crash Fire Accidents, FAA Technical Note, To Be Published.
56. Antimisting Kerosene Benefit-Cost Estimates for World Air Carrier Fleet, U.S. Carrier Fleet, and U.S. Commuter Fleet, Trans System Corporation, TS-129, December 1984.
57. Antimisting Kerosene Benefit-Cost System Software Model Design, Trans System Corporation Draft Report, November 1982.
58. Byrnes, H. S. and Klueg, E. P., Antimisting Fuel Additives Status Report, DOT/FAA/CT-TN85/22, July 1985.

**ANTIMISTING FUEL TECHNOLOGY**

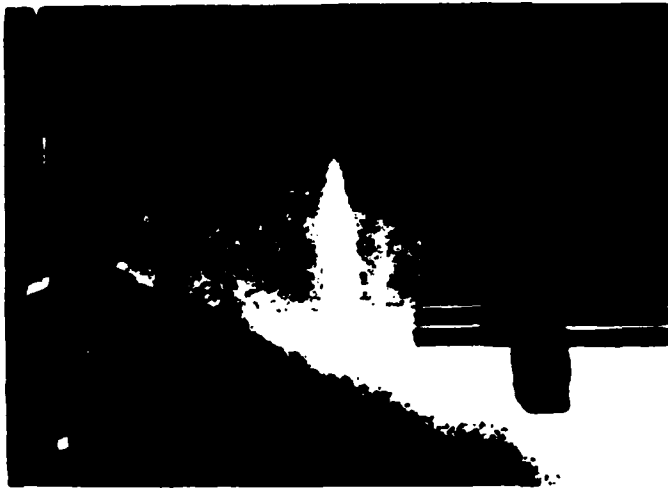
**BY**

**EUGENE P. KLUEG**

**FEDERAL AVIATION ADMINISTRATION  
TECHNICAL CENTER  
ATLANTIC CITY AIRPORT, N. J.**

**PRESENTATION AT:**

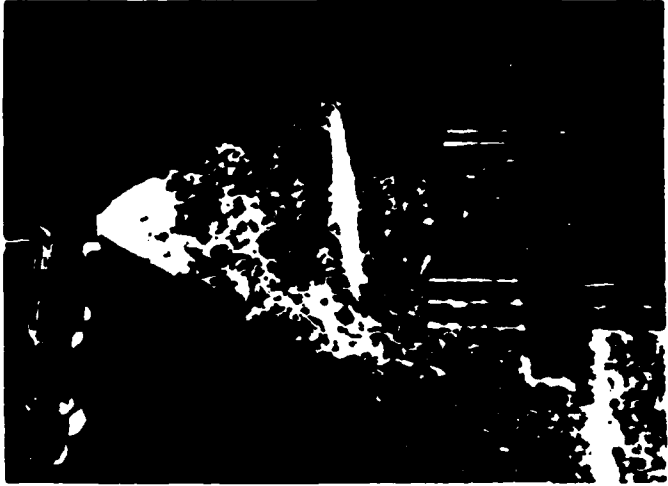
**FEDERAL AVIATION ADMINISTRATION  
FUEL SAFETY RESEARCH WORKSHOP  
ALEXANDRIA, VIRGINIA  
OCTOBER 29 - NOVEMBER 1, 1985**



**Jet A**



**Degraded FM-9**



**Undegraded FM-9**

*Spray Pattern With Delavan Injector - Cruise*

# **1978 AMK MEMORANDUM OF UNDERSTANDING**

## **UNITED STATES**

- **FEDERAL AVIATION ADMINISTRATION**
- **NATIONAL AERONAUTICS &  
SPACE ADMINISTRATION**

## **UNITED KINGDOM**

- **MINISTRY OF DEFENCE**
- **ROYAL AIRCRAFT ESTABLISHMENT**
- **DEPARTMENT OF INDUSTRY**
- **CIVIL AVIATION AUTHORITY**

# **SPECIAL AVIATION FIRE AND EXPLOSION REDUCTION ADVISORY COMMITTEE**

- **ESTABLISHED IN 1978 TO CONSIDER SURVIVABILITY  
IN FIRE-RELATED ACCIDENTS**
- **CONCLUSION - AMK COULD REDUCE POST-CRASH  
FIRE HAZARD**
- **RECOMMENDATION - EXPAND AMK RESEARCH**

# **ANTIMISTING KEROSENE (AMK) PROGRAM OBJECTIVES**

- **DETERMINE FEASIBILITY**
- **DEVELOP RECOMMENDATIONS FOR USE**
- **DEMONSTRATE EFFECTIVENESS**
- **ASSESS ECONOMICS**

## **AMK FEASIBILITY DECISION NOVEMBER 1980**

- **INCREASED RESISTANCE TO FUEL MIST FIRES**
- **NO TECHNICALLY UNSOLVABLE PROBLEMS**
- **FULL-SCALE TESTING INITIATED**

# **AMK PROGRAM ACCOMPLISHMENTS**

- **AMK CHARACTERIZATION**
- **AMK FLAMMABILITY**
- **AMK PRODUCTION**
- **AMK COMPATIBILITY**
- **FLIGHT TESTS**
- **IMPACT DEMONSTRATION**

# AMK CHARACTERIZATION

# **AMK CHARACTERIZATION ORGANIZATIONS**

- **FAA TECHNICAL CENTER**
- **SOUTHWEST RESEARCH INSTITUTE**
- **JET PROPULSION LABORATORY**
- **PRATT AND WHITNEY AIRCRAFT**

# **AMK RHEOLOGICAL STUDIES**

- **ANTIMISTING PROPERTIES**
- **FILTRATION PROPERTIES**
- **FLAMMABILITY PROPERTIES**
- **DEGRADATION LEVELS**
- **HEAT TRANSFER CHARACTERISTICS**
- **FRICTIONAL CHARACTERISTICS**
- **VISCOELASTIC PROPERTIES**

## **AMK HEAT TRANSFER CHARACTERISTICS**

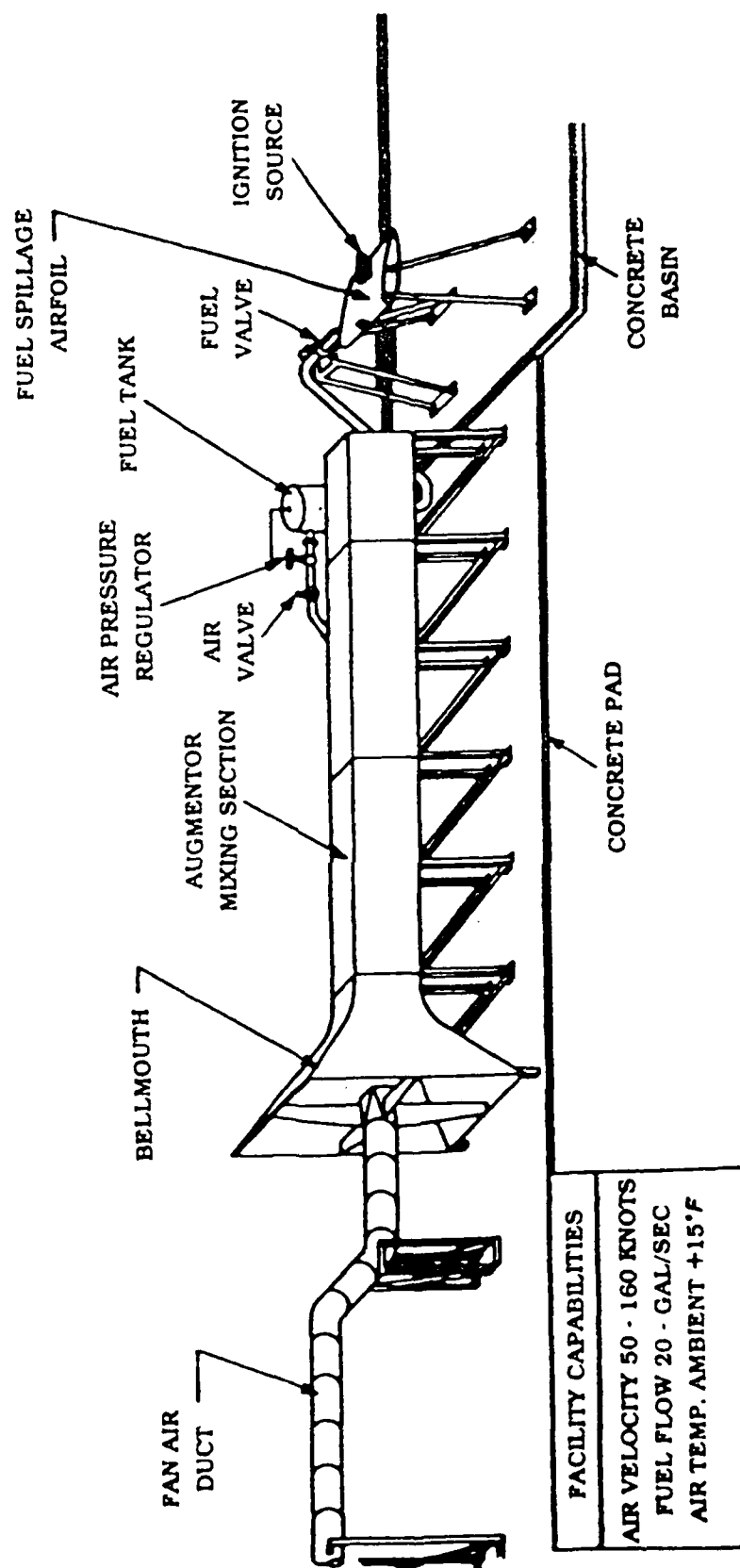
- **UNDEGRADED - SIGNIFICANTLY LESS THAN JET  
A AT HIGH FLOW RATES**
- **DEGRADED - AMK COEFFICIENT  $\approx$  90% OF JET  
A COEFFICIENT**

# AMK FLAMMABILITY

## **AMK FLAMMABILITY TESTS**

- **FAA FLAMMABILITY COMPARISON TEST APPARATUS**
- **SWRI SPINNING DISK**
- **JPL MINI-WING/IMAGE ENHANCEMENT**
- **FAA WING-FUEL SPILLAGE RIG**
- **NAVY CATAPULT CRASH TEST**

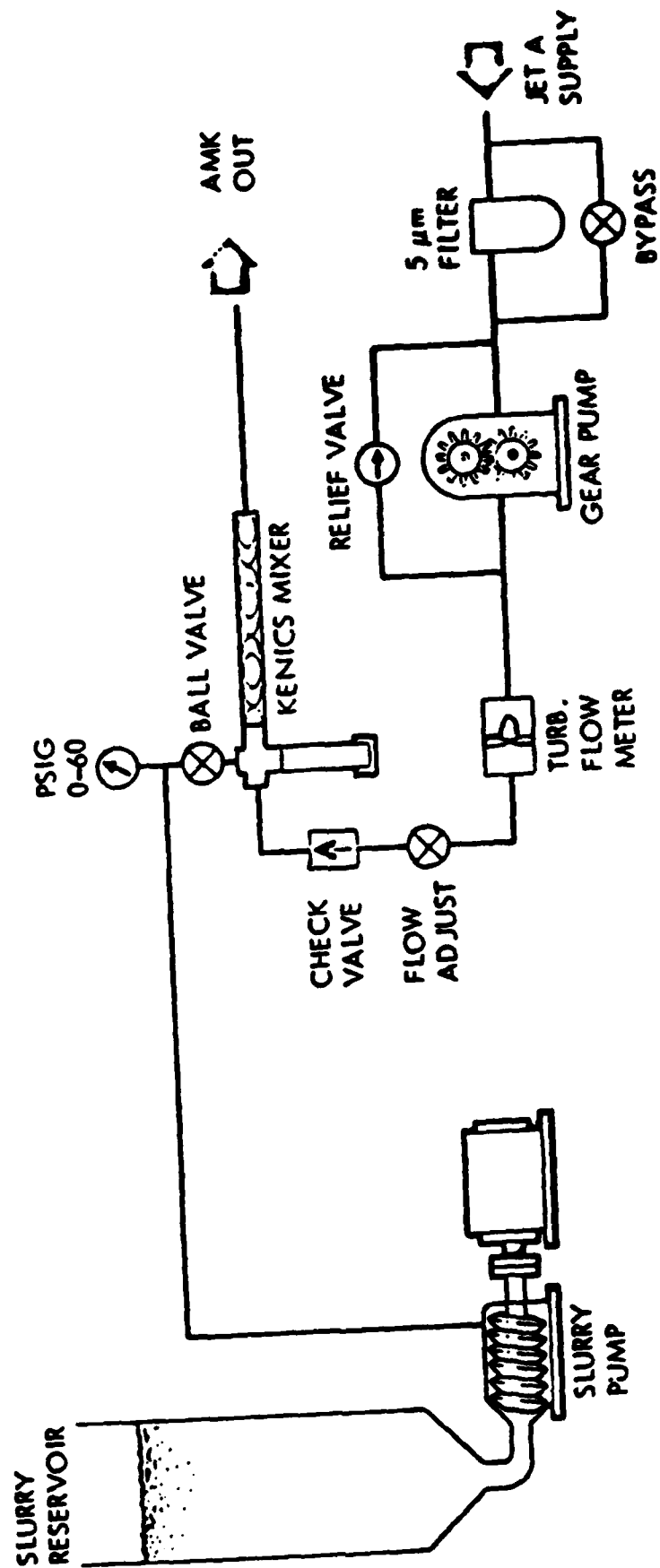
# MODIFIED FUEL-WING SPILLAGE TEST FACILITY



# NAVAL AIR ENGINEERING CENTER AMK AIRCRAFT CRASH TESTS

TEST NO	FUEL	SPEED
1	JET A	117 KNOTS
2	AMK	94 KNOTS
3	AMK	ABORTED
4	AMK	118 KNOTS
5	AMK	140 KNOTS
6	AMK	155 KNOTS

# AMK PRODUCTION



Schematic of the Inline Blender System

## **AMK IN-LINE BLENDING LIMITATIONS**

- **EQUILIBRATION TIME - 15 MIN. OR GREATER**
- **JET A TEMPERATURE - 0°C OR GREATER**
- **JET A AROMATICS - 12% OR GREATER**

# AMK COMPATIBILITY WITH FUEL ADDITIVES (MAXIMUM RECOMMENDED CONCENTRATIONS)

ADDITIVE	REACTION
ANTICORROSION	NONE
LUBRICITY	NONE
THERMAL STABILITY	NONE
METAL DEACTIVATOR	NONE
ANTI-ICING	PRECIPITATE
BIOCIDE	NONE

## **AMK COMPATIBILITY WITH WATER**

- **BULK WATER - PRECIPITATE**
- **WATER VAPOR & DISSOLVED WATER - HIGHER SATURATION & PRECIPITATE UNDER EXTREME CONDITIONS**

# AMK COMPATIBILITY

# **AMK COMPATIBILITY ORGANIZATIONS**

## **U.K.**

- **ROYAL AIRCRAFT ESTABLISHMENT**
- **PLESSEY AEROSPACE**
- **LUCAS AEROSPACE**
- **ROLLS-ROYCE**

## **U.S.**

- **TECHNICAL CENTER**
- **PRATT & WHITNEY AIRCRAFT**
- **GENERAL ELECTRIC**
- **LOCKHEED-GEORGIA**
- **DOUGLAS AIRCRAFT**
- **BOEING MILITARY AIRPLANE**
- **SOUTHWEST RESEARCH INSTITUTE**
- **JET PROPULSION LABORATORY**

## **AMK DEGRADER CONCEPTS**

- **ULTRAVIOLET LIGHT**
- **CATALYSIS**
- **ULTRASONICS**
- **LASERS**
- **CAVITATION**
- **HYDRO-MECHANICAL**
- **MECHANICAL**

## **AMK COMPATIBILITY RESULTS**

- **20 MINUTE EQUILIBRATION**
- **WATER VAPOR DOES NOT EFFECT FUEL**
- **MIST SUPPRESSION PROPERTIES RETAINED UNDER FLIGHT EXTREMES**
- **REDUCED PERFORMANCE OF SOME FUEL SUBSYSTEMS**
- **ENGINE PERFORMANCE NOT EFFECTED**
- **FILTRATION**
  - SOLUBLE GEL - LOW DEGRADATION LEVEL
  - INSOLUBLE GEL - UNEXPLAINED
  - FILM - JET A/AMK MIXTURE
- **COMBUSTION & EMISSIONS SENSITIVE TO DEGRADATION LEVEL**
- **ENDURANCE TESTING REQUIRED FOR CRITICAL ENGINE COMPONENTS**

## **ECONOMIC ASPECTS OF CONVERTING TO AMK**

- **EXTRA COST - 5% OF PRICE OF BASE FUEL**
- **2 TO 3 PERCENT INCREASE IN COST OF TICKET**
- **POTENTIAL BENEFITS - 135 LIVES SAVED PER YEAR**

## **STATUS OF AMK TECHNOLOGY**

- **IN-LINE BLENDING FEASIBLE**
- **HIGH FUEL MIST FIRE PROTECTION PROVIDED**
- **HIGHLY DEGRADED FUEL REQUIRED FOR ENGINE FUEL SYSTEM**
- **DEGRADATION FEASIBLE WITHOUT EXCESSIVE POWER**
- **CID EXCEEDED AMK DESIGN LIMITS**
- **FUTURE AMK IGNITION INVESTIGATIONS NEEDED**
- **FUEL SAFETY DEVELOPMENTS CONTINUE**
- **ADDITIONAL R&D REQUIRED TO MAKE AMK OPERATIONALLY ACCEPTABLE**

AMK FULL-SCALE TRANSPORT AIRCRAFT  
VALIDATION PHASE SUMMARY

BRUCE C. FENTON

FEDERAL AVIATION ADMINISTRATION

BACKGROUND/INTRODUCTION

The Federal Aviation Administration (FAA) has sponsored research and development of a technology that can minimize the fuel fire hazard during an impact-survivable aircraft crash by the introduction of a high molecular weight polymer into kerosene jet fuel. Research efforts have concentrated on a British-developed additive termed FM-9<sup>TM</sup>/AVGARD<sup>TM</sup> to demonstrate this technology. FM-9/Jet A antimisting kerosene (AMK) fuel is considered representative of a concept that is designed to be more resistant than neat Jet A to ignition and flame propagation in most crash scenarios and compatible with commercial transport airframe and engine fuel systems.

Public hearings by the FAA on fuel systems and cabin fire safety in 1977 prompted the FAA to examine the application of antimisting kerosene (AMK) fuel technology in transport aircraft. Results of ongoing research efforts in the United States as well as in the United Kingdom were encouraging. A program was expanded under a Memorandum of Understanding (MOU) between the United States and the United Kingdom in 1978 to cooperate in determining the technical feasibility of introducing the AMK concept into civil aviation. The principal participants under the MOU were the FAA and the National Aeronautics and Space Administration (NASA) in the United States and the Royal Aircraft Establishment (RAE) in the United Kingdom. A British-developed high molecular weight hydrocarbon additive concept manufactured by Imperial Chemical Industries (ICI Limited and ICI Americas, a U.S. subsidiary) called FM-9<sup>TM</sup> added to Jet A was used to demonstrate the state of the art in AMK fuel technology. In solution with Jet A, the FM-9 additive resists the normal tendency of the fuel to break up into fine mist droplets. This phenomenon is produced by the massive entanglement of the uncoiled long chain, organic polymer by the stress environment, thereby binding the base fuel into a population of fewer and larger drops than would exist without the additive. The presence of this coarser droplet field makes ignition either improbable or the propagation more difficult. Another important characteristic of FM-9 AMK was the apparent compatibility with aircraft fuel systems, a serious fault of previous fire suppressant modified fuels.

In conjunction with the MOU, the FAA developed a phased research and development program (Reference 1). In November 1980, the U.S./U.K. Management Committee concluded that the AMK concept of post-crash fuel mist fire suppression was feasible, and none of

the problems defined at that time was regarded as technically unsolvable. The Committee endorsed the continuation of the development phase. The FAA's successful completion of the major feasibility/development phase using FM-9/AMK at the laboratory- and large-scale levels established fuel characterization methods, performance specifications, flammability protection, blending techniques, and hardware compatibility. These positive results lead into a full-scale validation phase highlighted by transport aircraft ground and flight development tests and culminated in a Full-Scale Transport Controlled Impact Demonstration (CID) Program. An overview of the AMK program schedule is shown in Figure 1.

The following full-scale validation tests/results with CV880 and B720 aircraft are summarized: AMK blending at the aircraft; turbine engine installation, operation, and flight performance with a degrader; and the CID impact chronology.

#### AIRCRAFT FUEL SYSTEM MODIFICATIONS

The success of the flight degrader development and flight demonstration was the single most important (and complex) step towards achieving overall aircraft fuel/propulsion system compatibility. Due to the ambitious AMK program completion date of July 1984 (with the CID), the flight degrader development design utilized existing, flight proven components. The F101 engine centrifugal, augmentor pump was selected as the degrader and the C-5A aircraft auxiliary power air turbine motor was selected as the degrader/pump drive. The F101 has a maximum design flow capacity of 210 gpm, while the maximum fuel flow requirements of the CV880 and B720 engines are around 30 gpm. The fact that the pump was required to operate at, and usually below, this 30 gpm flow rate resulted in a significant fuel temperature rise. A recirculation loop through an air-liquid heat exchanger was provided to dissipate the added heat load. If the centrifugal pump were to be properly sized to the engine requirement, the temperature rise would be minimal. The centrifugal pump demonstrated by General Electric (GE) (Reference 2) featured a redesigned exit diffuser for optimum degradation. The air-turbine motor drive was powered continuously during the engine operation by compressor bleed air. The engine bleed air requirements to operate the degrader turbine drive were comparable to the turbo-compressor units used on these aircraft. The primary degrader system component equipment is shown in Figure 2. A throttling valve in the degrader/pump outlet was used to reduce fuel pressure to levels acceptable for the main engine fuel pump inlet. Fuel delivery from the tank boost pump can be bypassed around the degrader-pump through an external line and fast-acting valve that responds automatically to a degrader shutdown. The B720/JT3C test aircraft system

installation schematic is shown in Figure 3. The major installation differences between the two aircraft were the location of the air-fuel heat exchanger (CV880-ECS bay/B720-underwing pod) and the degrader/pump-drive assemblies (CV880-bottom of engine/B720-top of engine). Figure 4 is the right side view of the typical B720 degrader-engine nacelle installation. The particular hardware arrangements were driven by expediency and not of considered design. GE has indicated that the degrader-pressure regulating function can be incorporated at or within the main engine fuel pump in certificable systems, thus avoiding routing of additional external fuel lines around the engine would be avoided.

The CV880 aircraft was modified and instrumented so that the No. 3 engine and fuel tank would operate on AMK exclusively. The NO. 2 engine, operating on Jet A, served as the baseline. The B720 aircraft was modified and instrumented to operate with all four engines on AMK. The critical CV880 parameter measurements were displayed on a CRT and recorded on tape onboard the aircraft while the B720 raw data was telemetered to ground data acquisition systems for real time display and storage.

Both installations had the capability to provide degraded AMK for an engine start utilizing either a high pressure air ground cart, APU bleed or engine cross bleed. The degrader fuel system was prestarted and running prior to the engine start attempt on AMK.

Both aircraft featured the addition of a degrader control panel at the flight engineer station. Manual selection of degrader speed conditions was made at the panel by controlling inlet airflow from the compressor bleed to the air turbine motor/drive. An automatic mode could also be selected to permit speed setpoint condition in direct proportion to fuel flow demands. Figure 5 is a photograph of this installation in the B720 cockpit.

GE based its degrader design on the limiting conditions of both the CV880 flight tests and CID-B720 test aircraft flight envelope. GE employed an engine computer deck to determine, from known system component characteristics, the fuel temperature, pressure, and flow conditions at all points in the system. Calculation of the worst fuel and oil temperature conditions were modeled for the CV880 at 35,000 feet, Mach 0.8, idle power/minimum fuel flow operation with fuel tank temperature of 129.2 degrees Fahrenheit. The B720 limiting conditions were assumed to be sea level static, idle power with +80 degrees Fahrenheit fuel tank and +100 degrees Fahrenheit ambient air.

The evaluation of the installed degraded system to effectively restore AMK fuel to near normal Jet A properties was accomplished two ways. Degraded AMK sample analysis results were related to criteria that correlate to filterability and to engine combustor

nozzle performance. The following standards guidelines were used for the flight test programs.

- a. Filter Ratio (F.R.) = 1.2 Maximum
- b. Orifice Cup (Cup) = 7.0 Minimum

Reference 3 explains the significance of F.R. and Cup. In addition, Pratt and Whitney Aircraft (PWA) developed a procedure called transition velocity ( $V_T$ ), Reference 4, and established guidelines of 2.0-3.0 cm/sec minimum for the CID Program. This technique was developed as a more sensitive measurement than F.R. However, flight test experience showed that the engine fuel system response was not always consistent with the anticipated  $V_T$ . This was particularly true for high stress flow through filters and fuel control/fuel nozzle screens. Any flow/function compatibility anomaly with undegraded, marginally degraded, or other AMK fuel problem will immediately produce in gel buildup on one or more of these filters/screens. The gel buildup produces a characteristic dynamic pressure rise response across these filters/screens. To monitor this response, critical engine filters/screens were instrumented to measure pressure differential on both flight test aircraft. This approach provided a real time, on-line, active measurement of AMK-engine flow/function compatibility when compared to the reference Jet A baseline operation.

In both the CV880 and B720 programs, except for additional instrumentation, no modifications were made to the standard engine fuel system downstream of the degrader to accommodate for AMK compatibility.

Initial inline blending experience reported problems caused by poor polymer dispersion, slurry property variations, sensitivities to the broad Jet A specifications (i.e., water content). However, during the last 10-12 months leading up to and including the CID, when the number of gallons of AMK produced exceeded the total for the previous two years, there were no blending problems. The AMK fuel was consistently produced within specifications with gradually improving equilibration times. This was attributed to improved blending equipment and procedures, to consistently higher quality control standards for the slurry, and by monitoring the base Jet A quality.

The AMK fuel blend specifications established for the CID Program are listed below.

### AMK Characteristics 12 Hours After Blending

- Clarity (NTU) = 20 Maximum
- Orifice Flow Cup (ml/30 sec) = 1.7 Minimum to 2.3 Maximum
- Filter Ratio = 35 Minimum to 90 Maximum
- Polymer Solids Concentration = .30 Percent by Weight

Reference 5 provides a detailed explanation and shows the significance of these parameters. Actual CID blends prepared on the NASA Ames Dryden Flight Research Facility flight line reported characterization results at or within these specifications within 30 minutes to 1 hour.

The direct correlation between blend specification values and mist suppression/flammability resistance was maintained throughout the inline blend production experience. AMK blended with the 10 gpm unit at the FAA Technical Center and evaluated with the large-scale wing spillage test facility demonstrated fire suppression to 150 knots on blends of 15-60 minutes old. Continued inline blender runs at the FAA Technical Center on the 50 gpm unit and the 125 gpm unit demonstrated fire suppression to 160 knots on AMK blends 15-60 minutes old. Laboratory characterization results conducted within minutes after blending substantiated that these fire suppression properties exist within 15 minutes.

A demonstration of the degradability of inline, freshly blended AMK was conducted in the CV880 flight test program. The blender produced AMK directly into the empty No. 3 main wing tank, followed by No. 3 degrader/engine start within 15 minutes, and takeoff roll commencing within 30-40 minutes of blend completion. The degrader, engine, and filter/screen response was uneventful throughout the flight and post-flight inspections.

### FLIGHT TEST PERFORMANCE

#### CV880

The flight test objectives of the CV880 program were to demonstrate on a representative commercial aircraft.

- a. The effect of AMK on airframe/engine fuel system performance.
- b. The effect of aircraft fuel system and flight environment on the quality of AMK fuel.

- c. The feasibility of the prototype flight degrader design intended for use on the CID aircraft.

The CV880, with four GE CJ805 engines, was chosen as a representative commercial aircraft. The aircraft is no longer used by the major U.S. commercial carriers because of its relatively high fuel consumption per passenger seat-mile. Throughout the late 1950's and 60's, it was used extensively for U.S. commercial air travel and was a major competitor to the B707 and DC-8. It is presently used by foreign commercial air carriers and U.S. cargo transport. The CV880's similarity to the B720 makes degrader performance directly applicable to the CID aircraft. The CJ805 engine in the CV880 is a commercial derivative of the J79 military engine which was produced in large quantities. The fuel system from the main pump to the combustor is representative of large commercial aircraft engines.

The successful CV880 flight test program, through a series of on-the-wing engine ground runs and 14 test flights, accomplished the following.

- a. A total of 45 hours (30 flight hours) of degrader operation on AMK.
- b. No major degrader system hardware failures or design problems.
- c. Ground/flight tests operationally acceptable over a range of fuel supply temperatures from 0 to 90 degrees Fahrenheit.
  - (1) Ground starting acceptable at fuel ambient temperatures from 50 to 90 degrees Fahrenheit.
  - (2) Altitude relight at 10K to 30K feet and 0.5 to 0.6 flight Mach number. Same as Jet A baseline.
  - (3) Acceleration/deceleration at 10K to 40K feet. Same as Jet A baseline.
- d. Analysis of AMK fuel samples taken periodically from the No. 3 main tank showed that the fuel maintained the required mist-suppression qualities throughout the flight test environment.

In the initial 19 hours of CV880 ground/flight tests on AMK, there were instances of gel formation on filters and screens that have not been fully explained. This problem was not attributed to the degrader system effectiveness because the final 26 hours of AMK ground/flight test were completed without incident. The basic degrader hardware and operational procedures remained the

same throughout the entire flight program. Despite the occurrences of gel formation, aircraft/engine system operations were normal. One possible cause of this gel was fuel systems dirt and contaminants that had accumulated in the fuel system prior to the introduction of AMK. FM-9/AMK is known to be highly detergent. A similar experience of gellation occurred early in RAE development work when AMK was used in a Spey engine on a BAC111. As was the case in the CV880 aircraft, the gel diminished with operating time and eventually disappeared. During the period of gel formation, the inline blended AMK test fuel exhibited marginal equilibration times and end product qualities. During the final 26 hours of ground/flight tests, consistently high quality AMK fuel was produced.

Because of schedule slippages and redirected program priorities, fuel sloshing and tank moisture absorption tests were not performed to the degree desired. Degrader system performance tests with fuel to -40 degrees Fahrenheit were not conducted. Environmental flight conditions limited fuel temperatures to -6 degrees Fahrenheit.

Complete details of the entire CV880 flight degrader development investigation are included in Reference 6.

#### B720

To establish confidence in the reliability and performance of the four degrader/engine systems operating on AMK for the unmanned CID flight, a phased flight plan was conducted during the manned flights. The plan called for each degrader to be started, then run in level flight through speed accels and decels (CID flight profile), followed by a landing, and finally a takeoff while on Jet A. Multiple degrader/engine runs were accomplished as reliability was established. Once a degrader/engine was satisfactorily "qualified" on Jet A, the sequence was repeated for AMK fuel. When an engine operated on AMK, the center wing tank; override boost pump; and cross feed manifold system were dedicated to and used exclusively for AMK. During the course of the degrader/engine flights, only minor problems were identified in the areas of mechanical installation, instrumentation, degrader control, and operations procedures. Complementing these flights were a series of on-the-wing ground runs that established operational function before flights and resolved the problems identified in flight. Many problems and solutions experienced on the CV880 became directly applicable to the B720.

During a CID flight profile go-around climbout, a degrader inadvertently shutdown while operating on AMK. The engine continued operating normally on AMK for about one minute after which the flight engineer switched to Jet A. The pilot and

copilot observed no obvious differences with the engine while operating on degraded AMK, undegraded AMK, and Jet A. Other than the flight engineer's degrader control panel indications, the ground control instrumentation showed characteristic pressure rise across filters/screens. This pressure rise returned to normal immediately after the switch to Jet A. Post-flight inspection of these filters showed no residual evidence of shear induced gel. CV880 experience with a degrader shutdown while operating on AMK showed the filter(s) pressure rise returned to normal after the degrader was restarted while the engine continued to run on AMK.

The most significant problem consistently affecting all four B720 degrader systems was associated with the location of the degrader pump and the air-fuel cooler pod. The placement of the degraders on top of the engine and the cooler pod under the wing (elevated positions relative to the tank boost pump) made the fuel system very susceptible to air entrainment. This resulted in unstable degrader speed control and necessitated frequent and prolonged ground bleed operations. The CV880 installation locations at the bottom of the engine and in the ESC bay (lower wing root) resulted in relatively little air entrainment.

The installed flight steady state performance with AMK compared to Jet A is illustrated in Table 1. These data are representative of all four engines. Due to the installed raw data acquisition system accuracy and the uncertainty of true steady state conditions, these data can only provide a gross comparison of relative engine performance. The data shows that the engines operated comparably on both fuels. Table 2 presents the results of the AMK degradation levels as measured from fuel samples taken at a special engine boost pump inlet sampling fitting during ground runs. The range of values given at each fuel flow condition represents the spread of data for all four engines. Notice that the F.R. levels are slightly outside the flight program maximum requirement of 1.2. This fact illustrates the insensitivity of the fuel analysis criteria considering that the engine operation and fuel filter/screen response on AMK were the same as Jet A. Two out of five filter/screen pressure measurement results are given in Table 3 for a range of values on composite data for all four engines. For a given engine/filter/flow rate condition, the Jet A was identical to degraded AMK. Servo wash screen and P&D valve filter differential pressure and P&D valve manifold pressure measurements produced comparable results for AMK and Jet A.

AMK fuel samples taken from the center wing tank after the initial fill and prior to and after manned flights, Nos. 9 and 10, were used to measure blend quality history in the aircraft for a period of 20 days. The results of this analysis are shown for F.R. in Figure 6. Comparable results were reported for

TABLE 1

B720/JT3C ENGINE STEADY STATE PERFORMANCE  
ENGINE/DEGRADER #2

(Raw Data Corrected to Sea Level, Standard Day, Static Conditions)

N	(%)	EPR		EGT/ (°C)		WF/ (PPH)	
		JET A	AMK	JET A	AMK	JET A	AMK
70.5		1.1	1.1	315.7	315.7	1387	1410
90.7		1.6	1.6	421.3	418.2	4212	4244
97.7		2.2	2.2	563.4	553.2	7666	7693

TABLE 2

DEGRADER PERFORMANCE RESULTS

(COMPOSITE DATA)

	<u>F.R.</u>	<u>CUP</u> (ml/30 sec)	<u>VT</u> (cm/sec-min)
IDLE (1200 PPH)	1.25 - 1.33	7.4 - 7.5	1.5 - 2.9
4000 PPH	1.20 - 1.22	7.4 - 7.5	2.0 - 3.5
95% N <sub>2</sub> (7500 PPH)	1.10 - 1.25	7.5	3.0 - 4.0
Specifications	1.2 Max	7.0 Min	2.0 - 3.0 Min. (PWA Guidance)

TABLE 3

B720/JT3C-7 FUEL SYSTEM RESPONSE

(COMPOSITE DATA)

	FUEL PUMP INLET FILTER DP			FUEL PUMP INTERSTAGE FILTER DP		
	JET A	DEGRADED AMK	UNDEGRADED AMK	JET A	DEGRADED AMK	UNDEGRADED AMK
IDLE (1200 PPH)	0.5 - 1.0	0.5 - 1.0	2.0 - 3.0	0.2 - 0.5	0.2 - 0.5	0.75 - 1.0
4000 PPH	0.5 - 1.0	0.5 - 1.0		0.4 - 1.0	0.4 - 1.0	
95%N <sub>2</sub> (7800 PPH)	0.5 - 1.0	0.5 - 1.0	---	1.0 - 2.0	1.0 - 2.0	---

orifice cup and clarity. These data illustrate in nominal flight exposure the durability (resistance to unwanted degradation) and stability of the AMK in the wing tank.

By the completion of the manned ground and flight "qualifications" program the degrader system accumulated a total of 27.0 hours on Jet A (14.3 ground/12.7 flight) and 11.1 hours on AMK (7.1 ground/4.0 flight). Towards the completion of the manned flights, confidence in the system was high.

#### CID FLIGHT

The objectives of the AMK Program at the CID were to demonstrate that an antimisting fuel (FM-9/Jet A) can preclude ignition of an airborne fuel release and/or suppress the ignited fireball growth characteristics, while operating normally in a full-scale transport fuel/propulsion system during an air-to-ground controlled impact. The plan called for a remotely piloted Boeing 720 aircraft fueled with high quality inline-blended AMK to impact at a prepared site at a longitudinal speed of 155 knots (maximum) and immediately strike individual ground obstructions to produce multiple point wing tank ruptures generating a fuel spill of 20-100 gallons per second per rupture point. The fuel spill was to be exposed to one or more potential ignition sources for a minimum of 4-5 seconds exposure and/or to a minimum longitudinal slideout speed of 100 knots. Planned positive ignition sources included: engine operation/separation, airframe/engine electrical, simulated aft engine by open flame out fuselage tail cone, impact site slide out gravel, and electrically-powered approach landing light towers. Details of the impact site are shown in Figure 7. Actual pre-impact photographs of the impact site and a close-up of the wing openers are shown in Figures 8 and 9, respectively.

About 39 hours prior to the CID unmanned flight, approximately 11,400 gallons of AMK was inline-blended directly into 5 main wing tanks and 2 reserve tanks with a total capacity of 12,190 gallons. The time between blending/aircraft fueling and the CID flight was dictated by the preflight time line requirements and not AMK fuel considerations. Fuel samples were taken for each analysis from each tank during blending, at the completion of blending, and at numerous intervals up to within 3 hours of brake release. Fuel analysis results including independent cross checks on-site and off-site at Jet Propulsion Laboratory (JPL) showed that the blend displayed unquestioned quality, exceeding specification requirements. A summary of the CID AMK fuel analysis is given in Table 4.

Approximately one hour prior to brake release, the first of four degrader/engine pairs was started successfully to idle on AMK.

After brake release, all four degraders in the automatic mode responded normally to the takeoff fuel flow demand through roll, rotation, and climbout. Throughout the flight, the degraders continued to respond properly to fuel flow excursions through 2300 feet above ground level and approach to initial impact.

At initial impact, the left outboard engine hit a point 410 feet short of the planned impact point at approximately 148 knots. The attitude, roll, and yaw deviated significantly from the planned symmetrical controlled impact. The aircraft was in a left yaw of 13 degrees, rolled left at 13 degrees, and in a 1- to 2-degree nose down attitude at fuselage impact, approximately 1/2 second later. When the entire left wing and fuselage contacted the ground, telemetry data showed that both No. 1 and No. 2 degrader/engines spooled down to cutoff. Both engines separated at the pylon during the next 2 seconds of slideout, prior to reaching the wing opener obstruction area. By the time the aircraft reached the openers, it had slid 500 feet. The yaw angle had increased to 38 degrees left, and the longitudinal speed decayed to approximately 122 knots. At this point the initial wing opener impact occurred with the leading edge of the right wing almost perpendicular to the centerline of the impact zone. The telemetry data and instrumentation photography (exhaust plume disturbances on lakebed) confirmed that both right wing engines (No. 3/No. 4) were still operating at initial impact with the openers (Figure 10). The opener (third out from centerline) entered the nacelle and engine at the seventh stage of the low compressor. This opener then continued through the engine, stopping the rotor rotation within one revolution (Figure 10). At the same time, the aft engine mount failed as a result of the torsional moment transmitted through to the engine case. As the opener buried itself in the engine, the legs of the unit broke loose from the anchors, and the opener assembly rotated upward, cutting into the underside of the wing. Simultaneously, the wing opener, second from the impact centerline, tore through the underside of the wing just inboard of the No. 3 engine, causing sufficient damage to cause wing separation. The right wing fractured just inside the inboard engine. It rotated upward and forward, releasing most of the fuel from the inboard right main fuel tank (Figure 11). This tank contained approximately 2,150 gallons of fuel at impact.

The innermost wing opener on the right side cut through the inboard end of the right main inboard fuel tank and continued through the right center wing tank (which was not fueled) and into the wing box area of the fuselage. This opener is thought to be responsible for the damage to the fuselage keel beam structure.

TABLE 4

AMK FUEL BLEND ANALYSIS

<u>WING TANK</u>	<u>QUANTITY (GALS)</u>	<u>SOLIDS (%)</u>	<u>FLOW CUP (MLS/30 SEC)</u>	<u>FILTER RATIO</u>	<u>CLARITY NTU</u>	<u>JPL FIRE TEST</u>
#1 Reserve	254	0.31	1.6	65.0	6.0	Pass
#1 Main	2418	0.29	1.6	63.5	5.8	Pass
#2 Main	2164	0.30	1.6	62.5	5.8	Pass
Center Wing (Left)	1683	0.30	1.7	63.6	6.0	Pass
#3 Main	2194	0.30	1.7	70.6	5.9	Pass
#4 Main	2478	0.31	1.7	68.3	5.6	Pass
#4 Reserve	209	0.31	2.1	62.8	7.0	Pass
Specification(s)		$0.30 \pm .02$	1.7 - 2.3	35. - 90.	20 (Max)	

The outermost opener just nicked the outboard flap and then sliced through the aft underside of the fuselage, entering just under the right rear passenger door.

Because of the yaw, three of the four wing openers on the right side severely damaged the fuselage, opening holes through which fuel from the severed wing could enter the cargo area of the fuselage. Also, at fuselage impact, but prior to wing opener impact, the right forward cargo door opened, allowing additional fuel to enter this cargo area. A planview drawing of the aircraft damage caused by the wing opener cutters is shown in Figure 12.

The first ignition occurred 0.14 seconds after the initial impact of the engine with the wing opener. This ignition occurred on the inboard side of the No. 3 engine (Figure 13). It is not possible to determine the exact cause of this ignition. Most likely it was the release of combustion gases or flame from the ruptured engine or sparks generated by friction during the impact. The ignition was not caused by the exhaust plume of the engine.

The initial ignition was totally unlike that typically produced by AMK and probably involved misted lubricating oil, degraded AMK, and hydraulic fluid that were released under pressure when the engine was destroyed. When misted, each of these fluids tends to burn with the same degree of intensity that was evidenced by the primary ignition.

Considerable turbulence was being generated by the sideward slide of the fuselage and the release of large amounts of fuel from the severed wing tank that was rotating in front of the fuselage. The aircraft's yaw produced an area of intense recirculation in the immediate vicinity of the failed engine. AMK spilled into this region and was repeatedly sheared. This released fuel was also being exposed to the radiant and convective heat of the burning fuel as well as to the conductive heat transfer from hot engine metal surfaces for an extended time. Such extended residence at high temperature is known to cause AMK to vaporize and burn.

High speed photography shows that the airborne fireball engulfing the fuselage continued for approximately 8 seconds before going out. The effect of this exterior fuselage exposure to the fireball was minimal. The paint stripes and other markings appeared only slightly covered with soot; however, considerable burning continued in the lower portion of the fuselage.

The initial impression prior to viewing the photographic coverage was that AMK had failed to suppress the mist fireball and had, in fact, initiated a large pool fire. Careful review of the film

reveals that when the fireball lifted, there was no large pool fire. The film shows that the burning fuel that entered openings in the lower fuselage caused by the wing openers and the open cargo door was the cause of the fire that eventually destroyed the aircraft. There was a small pool fire in the area of the left wing tip that may have confused the initial picture. This fire was fed by fuel from the severed right wing that ended up adjacent to the left wing tip. However, it was extinguished by the fire fighters before becoming a serious threat to the fuselage.

A planview schematic of the impact site showing the aircraft ground track to rest is shown in Figure 14.

#### CONCLUDING REMARKS

The CV880 and B720 flight test programs and the CID established the following.

- a. The inline blending of AMK at the aircraft fueling point demonstrated consistently high fuel quality.
- b. The prototype degrader system demonstrated successful flight operation on a transport aircraft engine(s) with AMK fuel.
- c. Operation of turbojet engines on degraded AMK was comparable to the performance on Jet A under nominal flight conditions.
- d. Turbojet fuel system filter sensitivity to undegraded and degraded AMK is better understood.
- e. A representative, operational, full-scale transport aircraft with minor modifications can operate on an AMK fuel.
- f. The actual CID impact scenario deviated from the pretest requirements.
- g. There are accident scenario(s) where FM-9/AMK may not prevent a fuel spill fireball attachment to the wing/fuselage.

## REFERENCES

1. "Engineering and Development Program Plan Antimisting Fuel," FAA Technical Center, Report No. FAA-ED-18-4, September 1980.
2. Coffinberry, George A., Antimisting Fuel Degradation Investigation, DOT/FAA/CT-82/72, June 1982.
3. Klueg, E. P., S. L. Imbrogno, and B. C. Fenton, Aircraft Fuel Safety Research with Antimisting Fuels - A Status Report, DOT/FAA/CT-82/95, Presented at the AIAA/SAE/ASME 18th Joint Propulsion Conference, June 21 - 23, 1982, Cleveland, Ohio.
4. Fiorentino, A. J., and J. R. Planell, An Assessment of the Use of Antimisting Fuel in Turbofan Engines, Pratt & Whitney Aircraft Group, Report No. NASA CR-168081, October 1983.
5. Yavrouian, A. H., J. Ernest, and V. Sarohia, Antimisting Kerosene: Base Fuel Effects: Blending and Quality Control Techniques, DOT/FAA/CT-83/36, January 1984.
6. "Antimisting Fuel (AMK) Flight Degradation Development and Aircraft System Investigation," Program Technical Notes, Volumes I through IV, DOT/FAA/CTTN85/66-I, -II, -III, -IV.

# **ANTIMISTING FUEL FULL-SCALE TRANSPORT AIRCRAFT VALIDATION PHASE SUMMARY**

**BY BRUCE C. FENTON**



**Federal Aviation Administration  
Technical Center  
Atlantic City Airport, N.J. 08405**

**Proposed for Presentation at:  
The FAA Aviation Fuel Safety  
Research Workshop**

**October 29 thru Nov. 1, 1985  
Alexandria, Virginia**

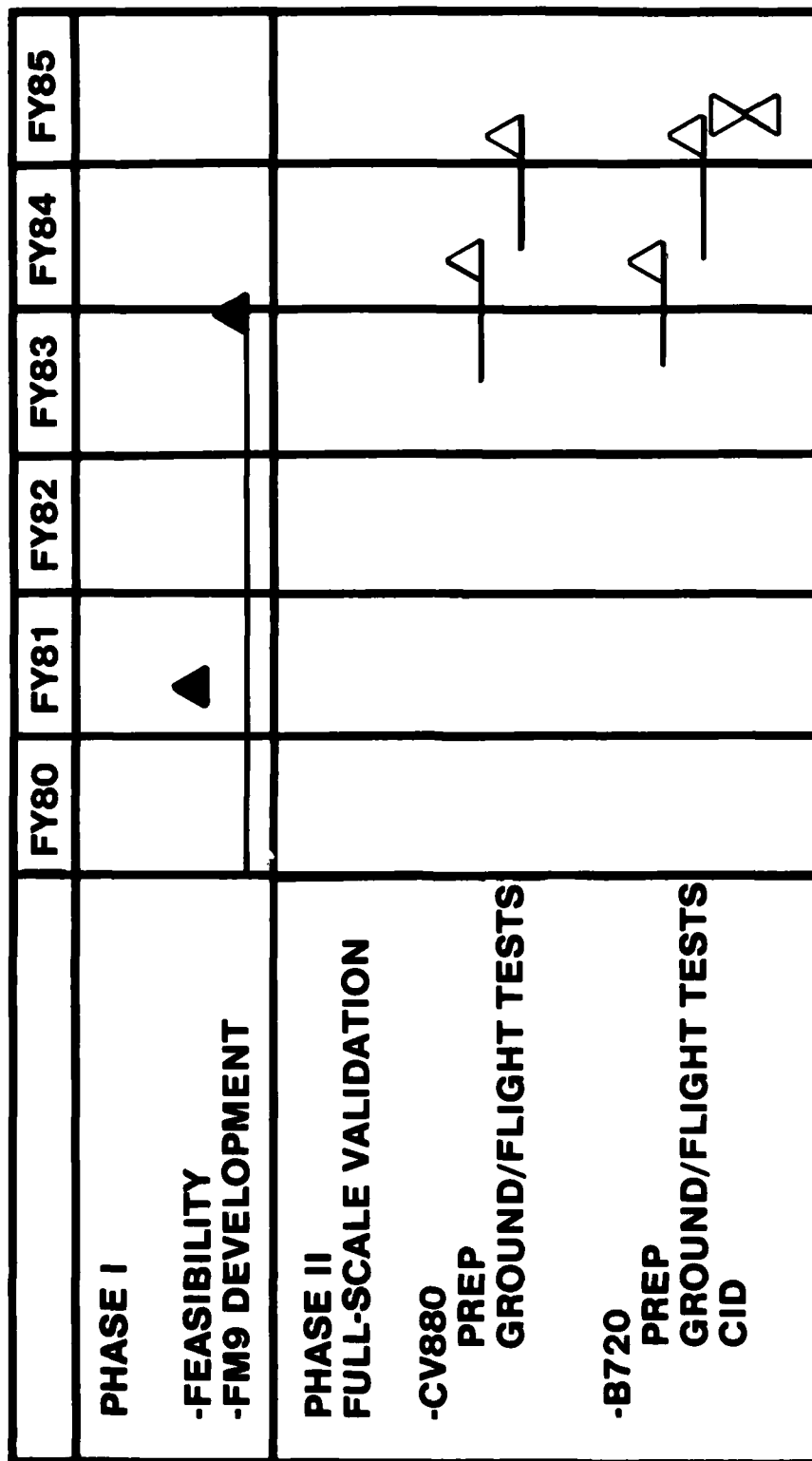


FIGURE 1. OVERALL ANTIMISTING FUEL PROGRAM SCHEDULE

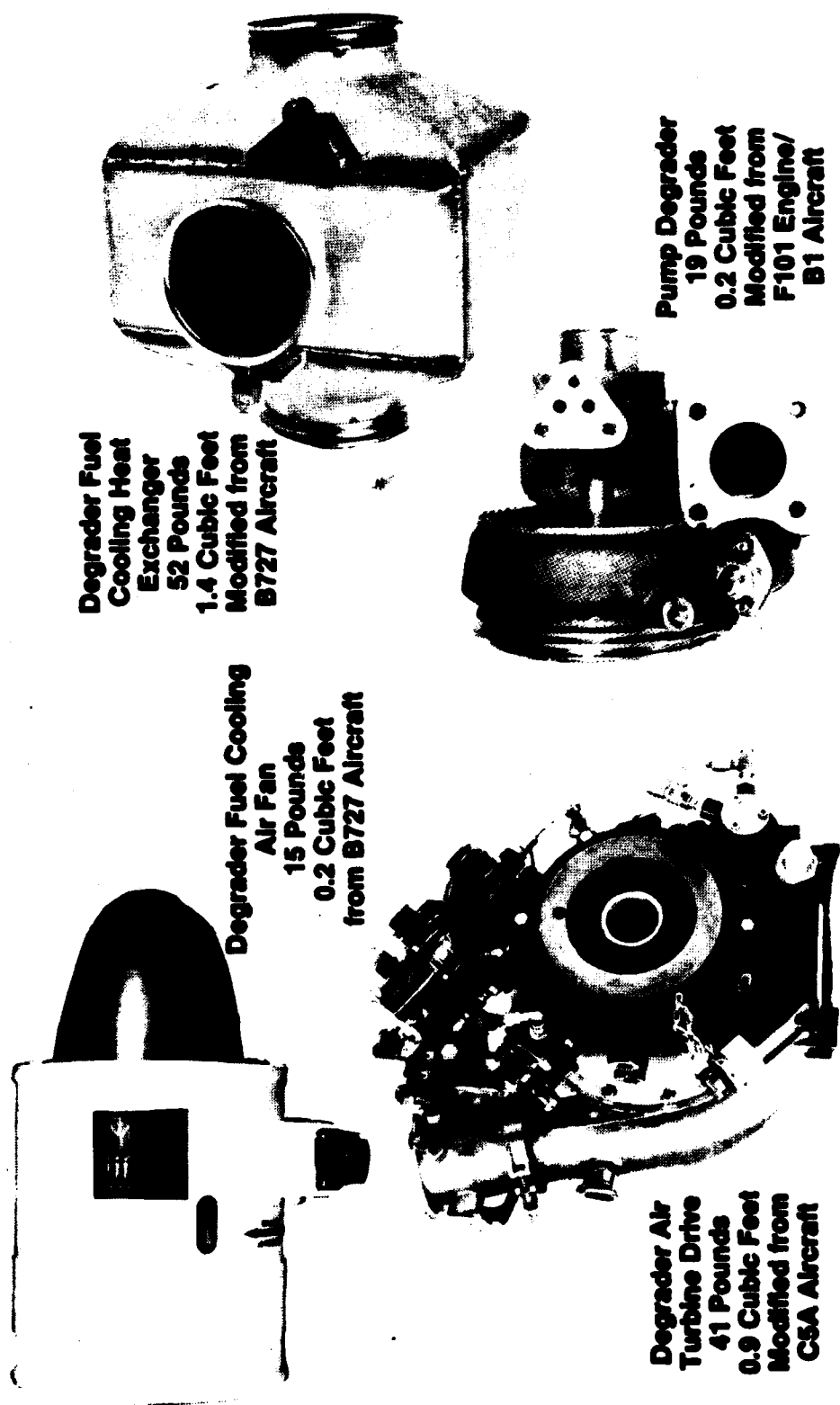


FIGURE 2. PROTOTYPE AMK DEGRADATION SYSTEM EQUIPMENT



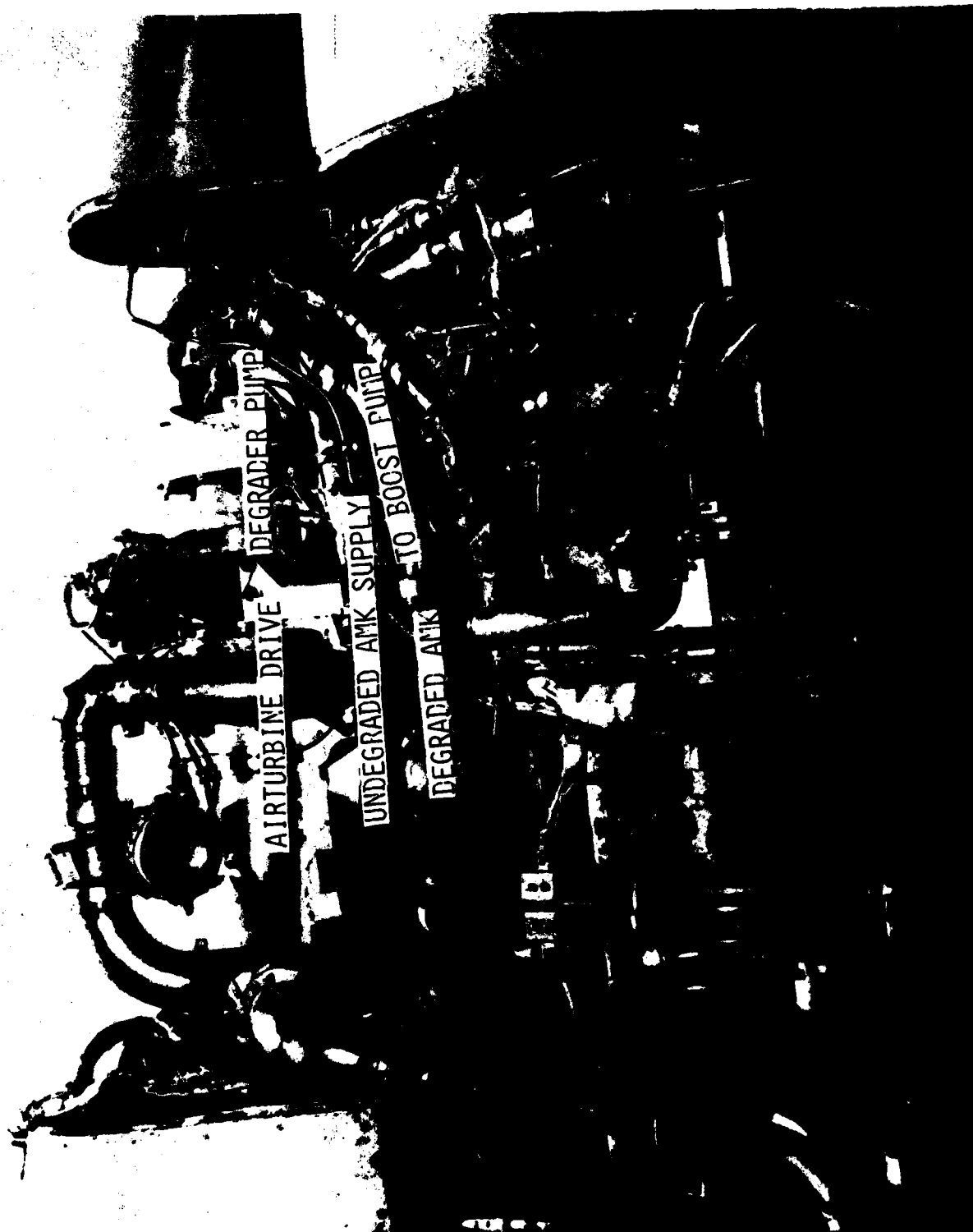


FIGURE 4. B720/JT3C FUEL DEGRADER INSTALLATION (RIGHT SIDE)

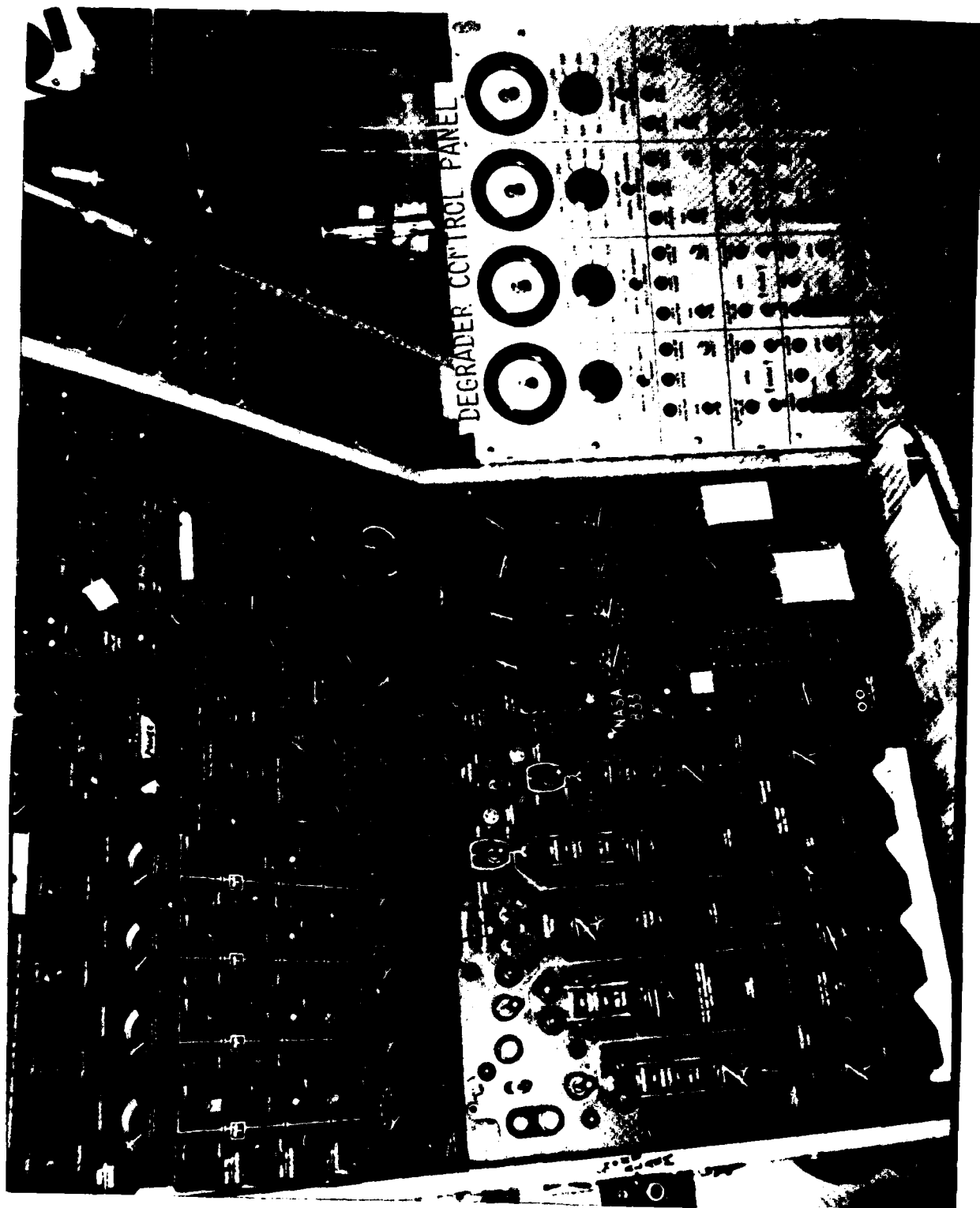


FIGURE 5. B720 FLIGHT ENGINEER STATION

# **CV880 FLIGHT DEGRADER INVESTIGATION**

## **OBJECTIVES**

- **DEMONSTRATE THE OPERATIONAL FEASIBILITY OF A PROTOTYPE FLIGHT DEGRADER DESIGN**
- **EFFECT OF AMK FUEL ON AIRFRAME/ENGINE FUEL SYSTEM PERFORMANCE**
- **EFFECT OF AIRCRAFT FUEL SYSTEM AND FLIGHT ENVIRONMENT ON AMK FUEL QUALITY**

# **ANTIMISTING FUEL PROGRAM**

## **CV880 FLIGHT TEST ACCOMPLISHMENTS**

- **45 HOURS DEGRADER OPERATION ON AMK 30 HOURS FLIGHT TEST**
- **NO MAJOR DEGRADER SYSTEM HARDWARE FAILURES OR DESIGN PROBLEMS**
- **GROUND/FLIGHT TESTS OPERATIONALLY ACCEPTABLE @ FUEL TEMPERATURES 0 TO +90°F**
  - GROUND STARTING (50 TO 90° F)
  - ALTITUDE RELIGHT: 10,000 TO 30,000 FEET  
0.5 TO 0.6 Mf
  - ACCEL/DECEL: 10,000 TO 40,000 FEET
- **IN TANK AMK QUALITIES MAINTAINED**
- **ENGINE FUEL FILTER/SCREEN RESPONSE**

# **ANTIMISTING FUEL PROGRAM**

## **B720 FLIGHT TEST ACCOMPLISHMENTS**

- **“QUALIFIED” FOUR DEGRADER SYSTEM INSTALLATIONS**
- **OPERATING TIME**
  - 27.0 HOURS JET A (14.3 GRND/12.7 FLT.)
  - 11.1 HOURS AMK (7.1 GRND/4.0 FLT.)
- **DEGRADER/ENGINE PERFORMANCE ACCEPTABLE**
- **ENGINE FUEL FILTER/SCREEN RESPONSE DEFINED**

# **B720/JT3C ENGINE STEADY STATE PERFORMANCE** **ENGINE/DEGRADER #2**

(Raw Data Corrected to Sea Level, Standard Day, Static Conditions)

N %	EPR		EGT (°C)		WF (PPH)	
	JET A	AMK	JET A	AMK	JET A	AMK
70.5	1.1	1.1	315.7	315.7	1387	1410
90.7	1.6	1.6	421.3	418.2	4212	4244
97.7	2.2	2.2	563.4	553.2	7666	7693

# **DEGRADER PERFORMANCE RESULTS (COMPOSITE DATA)**

	<u>F.R.</u>	<u>CUP (ml/30 sec)</u>	<u>VT (cm/sec-min)</u>
<b>IDLE (1200 PPH)</b>	<b>1.25 - 1.33</b>	<b>7.4 - 7.5</b>	<b>1.5 - 2.9</b>
<b>4000 PPH</b>	<b>1.20 - 1.22</b>	<b>7.4 - 7.5</b>	<b>2.0 - 3.5</b>
<b>95% N 2 (7500 PPH)</b>	<b>1.10 - 1.25</b>	<b>7.5</b>	<b>3.0 - 4.0</b>
<b>SPECIFICATIONS</b>	<b>1.2 max.</b>	<b>7.0 min.</b>	<b>2.0 - 3.0 min. (PWA GUIDELINES)</b>

TABLE 3

B720/JT3C-7 FUEL SYSTEM RESPONSE

(COMPOSITE DATA)

	FUEL PUMP INLET FILTER DP			FUEL PUMP INTERSTAGE FILTER DP		
	JET A	DEGRADED AMK	UNDEGRADED AMK	JET A	DEGRADED AMK	UNDEGRADED AMK
IDLE (1200 PPH)	0.5 - 1.0	0.5 - 1.0	2.0 - 3.0	0.2 - 0.5	0.2 - 0.5	0.75 - 1.0
4000 PPH	0.5 - 1.0	0.5 - 1.0		0.4 - 1.0	0.4 - 1.0	
95%N <sub>2</sub> (7800 PPH)	0.5 - 1.0	0.5 - 1.0	---	1.0 - 2.0	1.0 - 2.0	---

# **CID - AMK FUEL BLEND ANALYSIS**

WING TANK	QUANTITY (gals)	SOLIDS (%)	FLOW CUP (MLS/30 SEC)	FILTER RATIO	CLARITY NTU	JPL FIRE TEST
#1 RESERVE	254	0.31	1.6	65.0	6.0	PASS
#1 MAIN	2418	0.29	1.6	63.5	5.8	PASS
#2 MAIN	2164	0.30	1.6	62.5	5.8	PASS
CENTER WING (LEFT)	1683	0.30	1.7	63.6	6.0	PASS
#3 MAIN	2194	0.30	1.7	70.6	5.9	PASS
#4 MAIN	2478	0.31	1.7	68.3	5.6	PASS
#4 RESERVE	209	0.31	2.1	62.8	7.0	PASS
SPECIFICATION(S)		0.30 ±.02	1.7-2.3	35.-90.	20 (max)	

AD-A168 784

PROCEEDINGS OF FUEL SAFETY WORKSHOP HELD AT ALEXANDRIA  
VIRGINIA ON 29 OCT. (U) FEDERAL AVIATION ADMINISTRATION  
WASHINGTON DC PROGRAM ENGINEE. 31 DEC 85

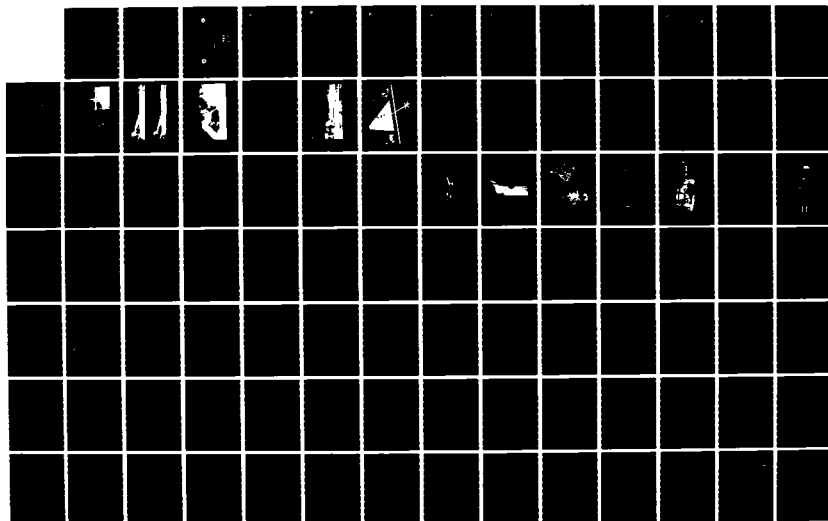
2/4

UNCLASSIFIED

DOT/FAA/PM-86/13

F/G 21/4

ML





۷۱۳۷

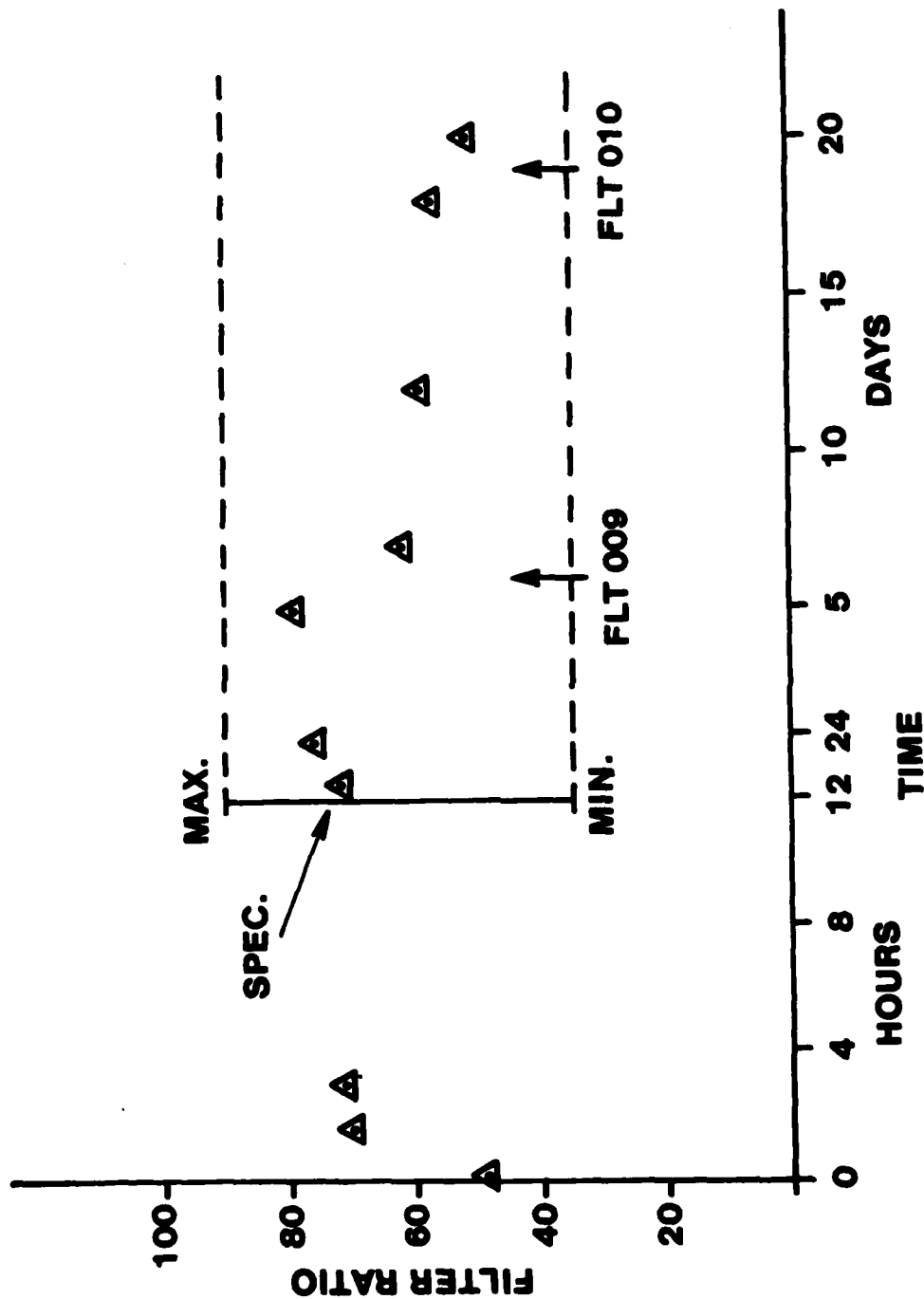
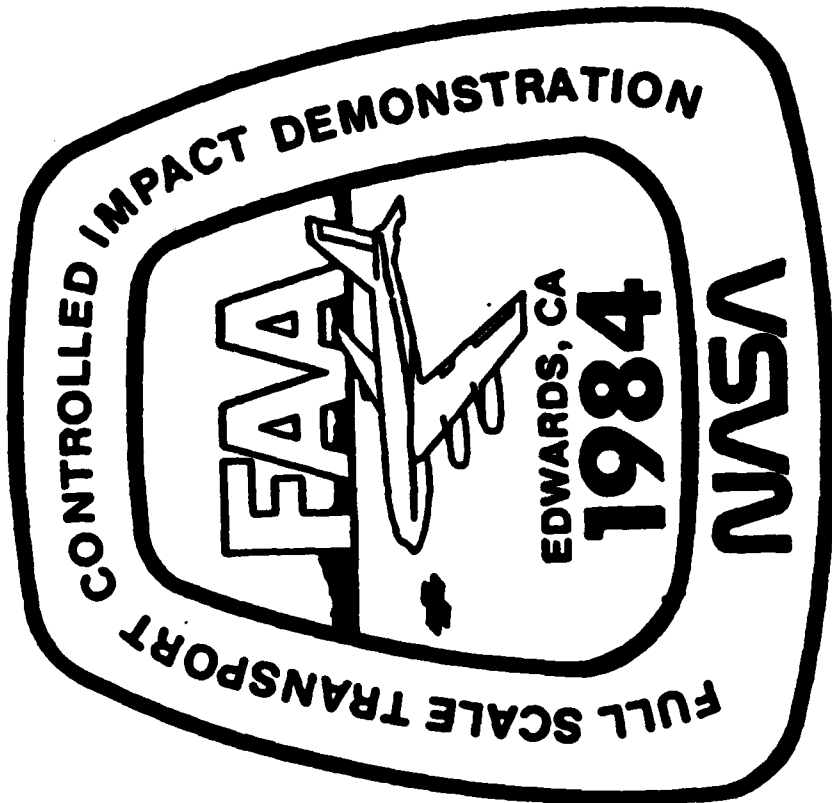


FIGURE 6. FILTER RATIO VERSUS TIME SINCE BLEND COMPLETE

**NATIONAL AERONAUTICS  
AND  
SPACE ADMINISTRATION**



**FEDERAL AVIATION  
ADMINISTRATION**





## **FULL-SCALE TRANSPORT CONTROLLED IMPACT DEMONSTRATION PROGRAM**

### **PURPOSE AND OBJECTIVES**

#### **PURPOSE:**

- **DEMONSTRATE AND VALIDATE TECHNOLOGY THAT CAN IMPROVE  
TRANSPORT AIRCRAFT OCCUPANT CRASH SURVIVABILITY THROUGH:**
  - REDUCED POST-CRASH FIRE HAZARD
  - IMPROVED CRASH IMPACT PROTECTION

#### **OBJECTIVES:**

- **VERIFY AN ANTIMISTING FUEL THAT CAN PRECLUDE MISTING AND  
DEMONSTRATE AN OPERATIONAL FUEL/PROPULSION SYSTEM**
- **ACQUIRE STRUCTURAL BASELINE DATA IN ORDER TO BETTER UNDERSTAND  
TRANSPORT CRASH BEHAVIOR**
- **DEMONSTRATE THE EFFECTIVENESS OF EXISTING/IMPROVED  
SEAT/RESTRAINT AND STRUCTURAL SYSTEMS**
- **OBSERVE CABIN FIRE SAFETY FEATURES PERFORMANCE**

## **CID EXPERIMENT OBJECTIVES**



- **ANTIMISTING KEROSENE (AMK)**
  - VERIFY AMK CAN PRECLUDE IGNITION UPON IMPACT.
  - DEMONSTRATE AMK IN AN OPERATIONAL FUEL/PROPULSION SYSTEM
- **STRUCTURE (FUSELAGE, WING, FLOOR) -**
  - EXAMINE STRUCTURAL MECHANISMS AND CORRELATE ANALYTICAL PREDICTIONS
  - PROVIDE BASELINE METAL CRASH DATA TO SUPPORT FAA AND NASA COMPOSITE CRASH DYNAMICS RESEARCH
  - DEFINE DYNAMIC FLOOR PULSE FOR SEAT/RESTRAINT SYSTEM STUDIES
- **SEAT/RESTRAINT SYSTEM -**
  - ASSESS REGULATORY CRITERIA
  - EVALUATE PERFORMANCE OF EXISTING, IMPROVED, AND NEW LIGHTWEIGHT SEAT CONCEPTS
  - EVALUATE PERFORMANCE OF NEW SEAT ATTACHMENT FITTINGS

## **CID EXPERIMENT OBJECTIVES (CONT'D.)**



- **STOWAGE COMPARTMENTS/GALLEYS**
  - EVALUATE EFFECTIVENESS OF EXISTING/IMPROVED RETENTION MEANS
- **ANALYTICAL MODELING -**
  - VALIDATION OF FAA "KRASH" AND NASA "DYCAST" MODELS TO TRANSPORT AIRCRAFT
  - VERIFY PREDICTED CRASH TEST IMPACT LOADS
- **CABIN FIRE SAFETY -**
  - OBSERVE SEAT BLOCKING LAYERS
  - BURN-THROUGH RESISTANT WINDOWS
  - AND LOW-LEVEL EMERGENCY LIGHTS PERFORMANCE

## **CID EXPERIMENT OBJECTIVES (CONT'D.)**



- **FLIGHT DATA AND COCKPIT VOICE RECORDERS -**
  - DEMONSTRATE/EVALUATE PERFORMANCE OF NEW FDR/CVR SYSTEMS
  - DEMONSTRATE USEFULNESS FOR ACCIDENT INVESTIGATION ANALYSIS
- **FLIGHT INCIDENCE RECORDER/CRASH POSITION LOCATOR -**
  - DEMONSTRATE/EVALUATE PERFORMANCE OF THE EJECTABLE  
U.S. NAVY/NAVAL AIR TEST CENTER (NATC) SYSTEM
- **HAZARDOUS MATERIALS PACKAGE -**
  - DEMONSTRATE PERFORMANCE OF PACKAGES IN AN  
IMPACT ENVIRONMENT
- **POST-IMPACT ACCIDENT INVESTIGATION ANALYSIS -**
  - ASSESS ADEQUACY OF CURRENT NATIONAL TRANSPORTATION  
SAFETY BOARD (NTSB) FORMS AND INVESTIGATION PROCEDURES



- 98

# **ANTIMISTING FUEL PROGRAM**

## **CID FLIGHT**

### **OBJECTIVES**

- **DEMONSTRATE THAT AMK CAN RESIST AIRBORNE FUEL MIST IGNITION AND/OR SUPPRESS FIREBALL GROWTH CHARACTERISTICS**
- **DEMONSTRATE FULL-SCALE TRANSPORT FUEL/PROPULSION SYSTEM OPERATION ON AMK**

# **ANTIMISTING FUEL PROGRAM (CONT'D.)**

## **REQUIREMENTS**

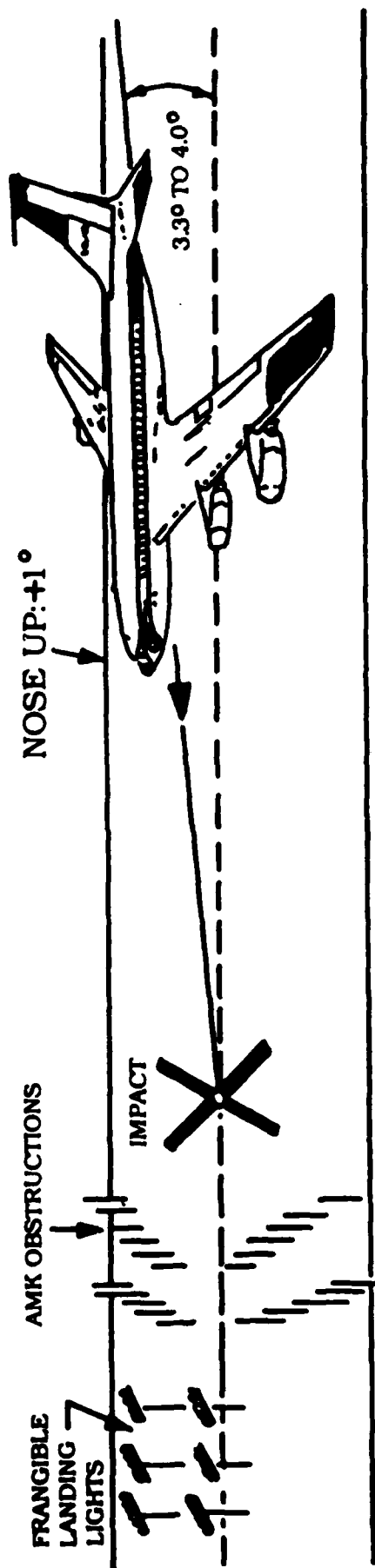
- **FULL-SCALE TRANSPORT AIR-TO-GROUND IMPACT**
- **LONGITUDINAL SPEED AT IMPACT 155 KNOTS (MAX)**
- **MULTIPLE POINT WING TANK FUEL RELEASE OF  
20-100 GALLONS/SECOND**
- **FUEL DISPERSION EXPOSED TO VERIFIABLE  
IGNITION SOURCE(S) FOR 4 SECONDS (MIN.)  
AND/OR TO A MINIMUM LONGITUDINAL SPEED AT  
100 KNOTS**



## FULL-SCALE TRANSPORT CONTROLLED IMPACT DEMONSTRATION PROGRAM

### IMPACT SCENARIO

- REPRESENTATIVE OF: A SURVIVABLE ACCIDENT
- CRASH: AIR-TO-SURFACE; FINAL APPROACH/LANDING, MISSED APPROACH, AND/OR TAKEOFF ABORT
- AIRCRAFT CONFIGURATION: LANDING GEAR RETRACTED, FLAPS, SPOILERS (AS REQUIRED), SYMMETRICAL/STABILIZED
- SINK RATE:  $17^{+0}_{-2}$  FPS
- GLIDE PATH:  $3.3^{\circ}$  TO  $4.0^{\circ}$
- LONGITUDINAL VELOCITY:  $150^{+5}_{-0}$  KNOTS
- GROSS WEIGHT: 175-195,000 POUNDS



## CID OPERATING RULES



- FROM BRAKE RELEASE, THROUGH FLIGHT PROFILE, DOWN TO 400' ON FINAL APPROACH:
  - ANY EXPERIMENTOR, SYSTEMS SUPPORT TEAM, OR RPV PILOT- CAN CALL A "GO-AROUND"
  - DECISION THEN MADE FOR ANOTHER ATTEMPT OR ABORT TO LAND
- BETWEEN 400' DOWN TO 150' ON FINAL APPROACH:
  - ONLY RPV PILOT CAN CALL A "GO-AROUND"
- FROM 150' TO IMPACT:
  - ACTIVATE PHOTO BATTERIES, DAS RECORDERS/CAMERAS, AND LAKEBED CAMERA SYSTEM
  - RPV PILOT MUST CONTINUE TO IMPACT

# CID Impact Flight Profile

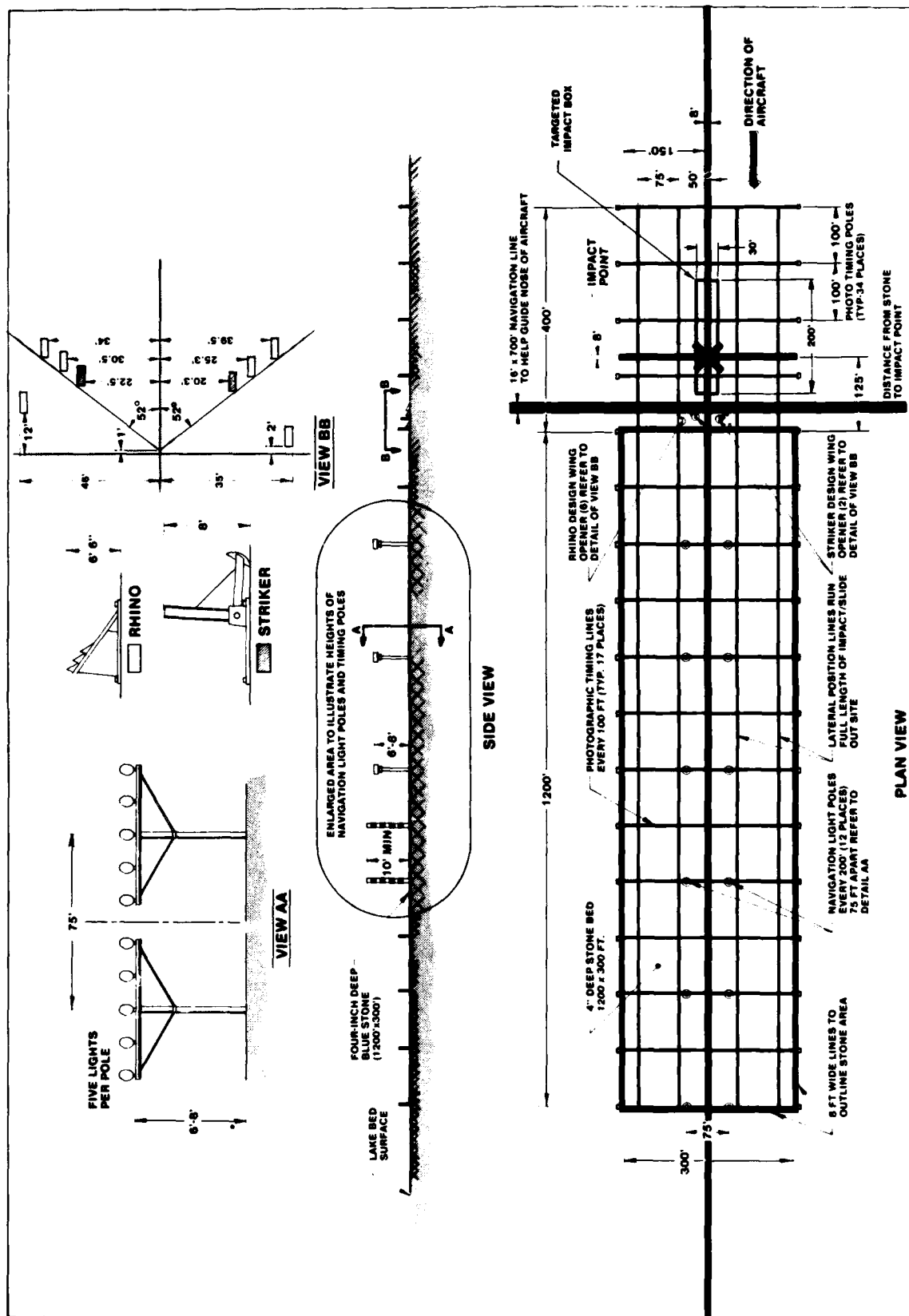


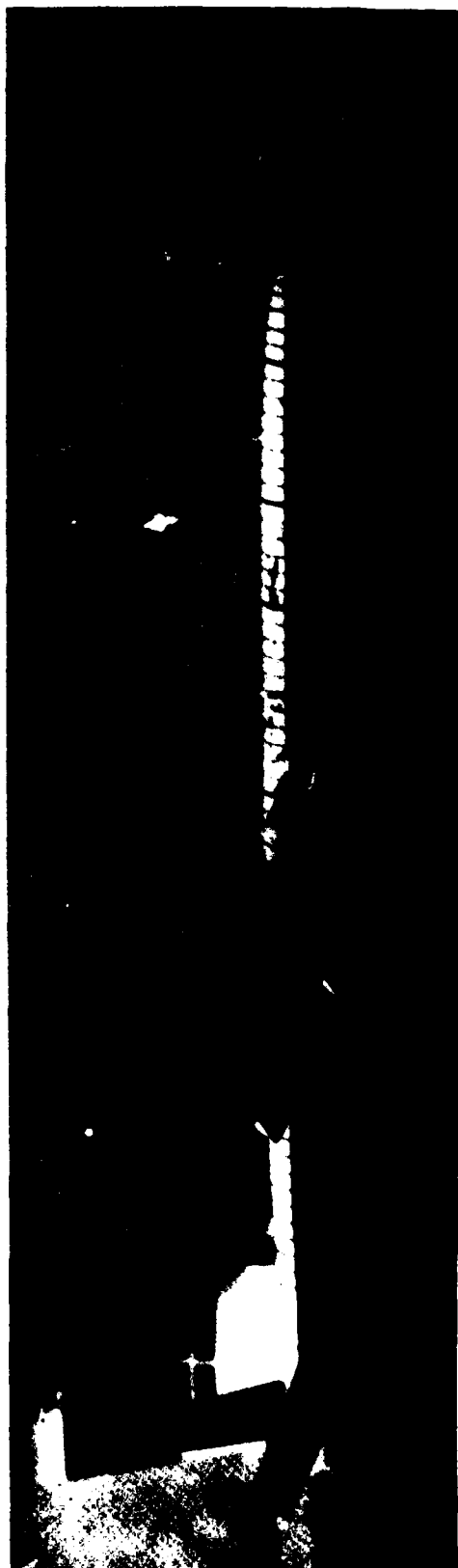
FIGURE 7. CID IMPACT SITE



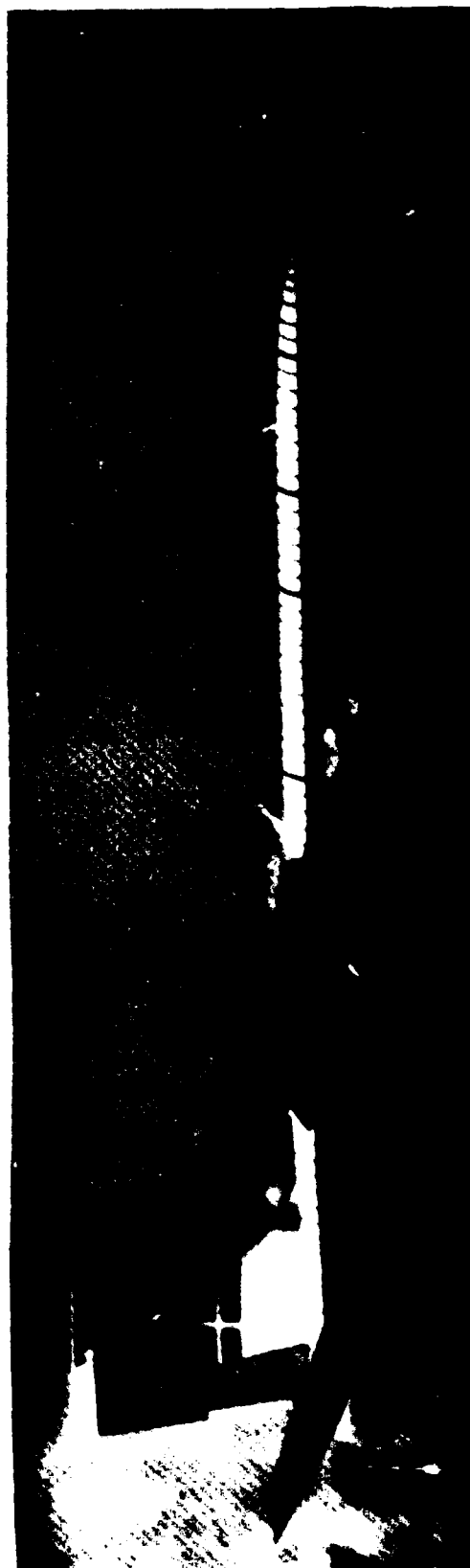
FIGURE 8. PRE-CID IMPACT SITE  
(AERIAL VIEW)



FIGURE 9. WING OPENERS  
(GROUND VIEW)



A. OPENER INTO 7TH COMPRESSOR ROTOR



B. OPENER THRU NO. 3 ENGINE

FIGURE 10. CID B720 NO. 3 ENGINE PENETRATED BY WING OPENER



FIGURE 11. CID B720 RIGHT WING SEPARATION (GROUND LEVEL, HEAD-ON VIEW)

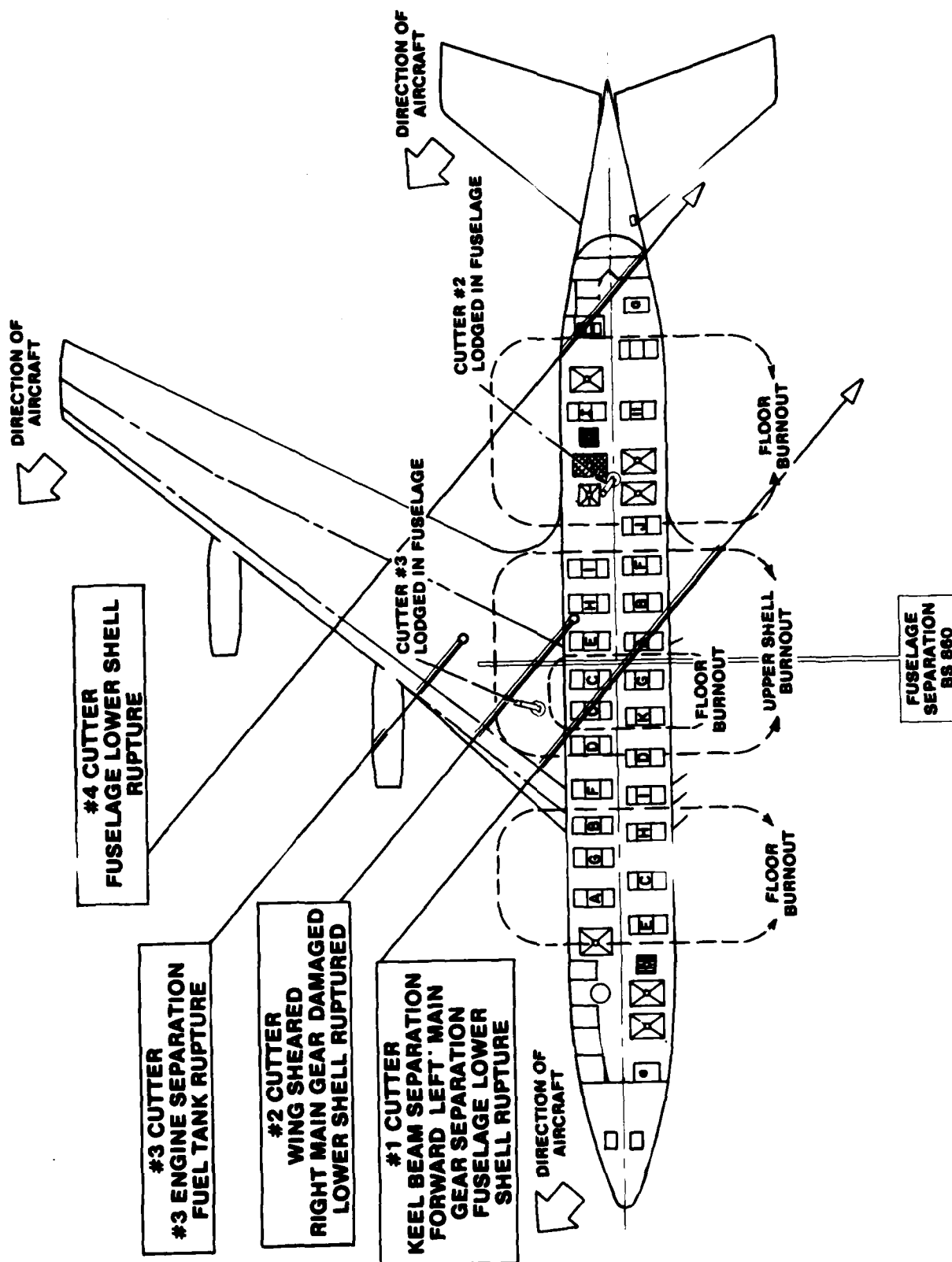


FIGURE 12. CID FIRE/STRUCTURAL DAMAGE

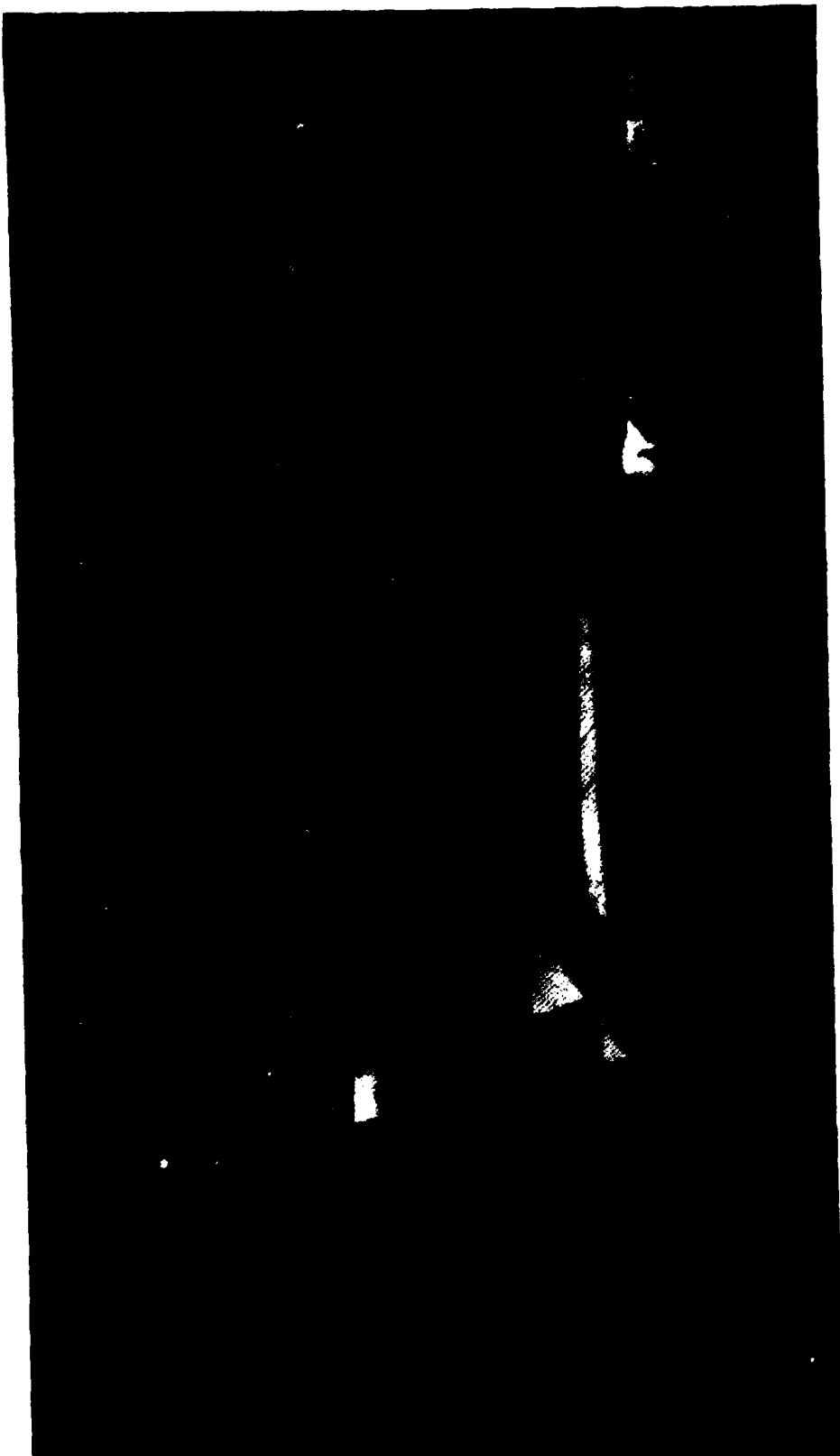


FIGURE 13. CID B720 PRIMARY IGNITION AT NO. 3 ENGINE (GROUND LEVEL, RIGHT-REAR VIEW)

# FULL-SCALE TRANSPORT CONTROLLED IMPACT DEMONSTRATION

IMPACT/SLIDEBOUT SITE  
WINDWARD SIDE OF RUNWAY

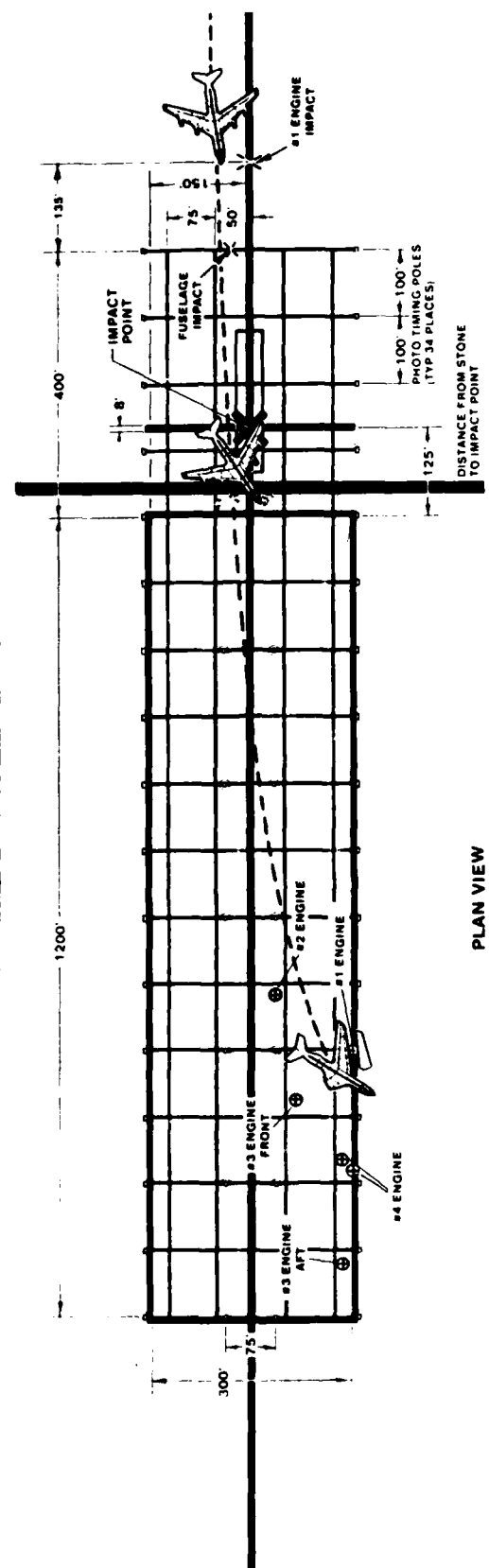
- LEGEND
- LANDERS SURFACE
  - LATERAL POSITION AND  
THRESH LINES
  - FOUR-INCH DEEP GROVE
  - GREEN TOLERANCE FOR  
IMPACT AREA
  - IMPACT POINT

LANDING LIGHTS

WING OPENER  
OBSTRUCTIONS

# CID-TIME/EVENT CHRONOLOGY

TIME (SECONDS)	EVENT	AIRCRAFT		LOCATION LONGITUDINAL/LATERAL (FEET)
		GROUND SPEED (KNOTS-APPROX.)		
0	INITIAL CONTACT WITH GROUND - #1 ENGINE	148.		0./0.
0.5	FUELAGES IMPACT	148.		135./20.(rt.)
1.8	WING OPENER MAKES INITIAL CONTACT WITH # 3 ENGINE	122.		500./40.(rt.)
1.9	#3 ENGINE FIRE INITIATED	122.		550./40(rt)
9.0	TO REST	0.		1385/250(lf.)
11.5	FIRE/SMOKE LIFTS OFF FUSELAGE	0.		1385/250(lf.)
90.	CRASH/FIRE RESCUE ARRIVE	0.		1385/250(lf.)



**FIGURE 14. AIRCRAFT GROUND TRACK AT IMPACT SITE**

# **ANTIMISTING FUEL PROGRAM**

## **CONCLUSIONS**

- **INLINE BLENDING OF AMK DEMONSTRATED AT AIRCRAFT FUELING POINT**
- **PROTOTYPE DEGRADER SYSTEM DEMONSTRATED SUCCESSFULLY IN FLIGHT**
- **TURBOJET ENGINE PERFORMANCE DEMONSTRATED TO BE COMPARABLE TO JET A**
- **FUEL SYSTEM FILTER/SCREEN(S) SENSITIVITY DEMONSTRATED**

# **ANTIMISTING FUEL PROGRAM**

## **CONCLUSIONS (CONT'D.)**

- **FULL-SCALE TRANSPORT CAN OPERATE ON AMK**
- **CID CRASH IMPACT DEVIATED FROM PRE-TEST REQUIREMENTS**
- **FM-9/AMK MAY NOT PREVENT FIREBALL WING / FUSELAGE ATTACHMENT IN SOME ACCIDENT SCENARIO(S)**

FAA ANTIMISTING FUEL PROGRAM  
POST CONTROLLED IMPACT DEMONSTRATION (CID) ANALYSIS

WILLIAM T. WESTFIELD

Ignition and Continuous Burning Analysis

Over the seven years since the Federal Aviation Administration program on antimisting fuel was formalized, practically all of the engineering problems identified as having need of solution in 1978 have been successfully solved. Prominent among these were the need for a method of inline blending of the antimisting additive into the Jet A kerosene as the aircraft is being fueled, or refueled, and the need for an efficient method of degradation (or neutralization) of the antimisting additive by an engine mounted device to allow efficient engine operation. Several technical problems have not been actually demonstrated as having been solved, such as the maintenance of boost and jet transfer pump efficiencies or heat transfer properties, but sufficient data is in hand that application of the industry skills in this area lead to a conclusion that a successful solution to the problem is in the offing. The presence of bulk water remains a technical problem and can only be addressed by rigorous application of housekeeping procedures at airports.

Nevertheless, the FAA has taken the position that the concept of the use of antimisting fuel has been proven. With the successful flight testing of an aircraft fully fueled by the antimisting fuel, the attempt to demonstrate its ability to control the post-crash fire was undertaken in the CID.

The CID was designed to subject the aircraft and fuel to a severe but impact-survivable force. Impact speed was to be 150 knots, nominally, with approximately 17 feet per second sink rate, a slightly nose-up attitude to produce a major vertical pulse to the fuselage just aft of the wing box, and with minimum yaw or roll (to assure symmetry of the crash impulse).

As it occurred, the CID met the horizontal speed and vertical sink rate requirements but impacted with a slightly nose down attitude, and 13 degrees of left roll and 13 degrees of left yaw. Also, the initial impact at these conditions was 50 feet to right of center, about 475 feet short of the planned; and when the aircraft reached the planned impact point, it had decelerated to about 122 knots and the left yaw had increased to 38 degrees. (See Figure 1.)

The planned impact area had been prepared with eight heavy steel cutters, four on each side of centerline, which were designed to rupture the wing for positive fuel release. As the CID actually occurred, these cutters were impacted not in a head-on motion, but with the aircraft moving sideways into the zone. The yawed

condition, as it developed, was the most critical to the CID impact. The third cutter from center in the right hand bank of four entered the right inboard engine of the CID aircraft at the seventh stage of the compressor, stopping this engine's rotation in about one third of a revolution. The cutter then broke loose from its desert floor mounting and rotated upward, doing massive damage to the underside of the number three wing tank. The second cutter from center also cut through the underside of the wing and the combination of these two sets of damage was sufficient to cause the wing to sever inboard of the number 3 engine. All four cutters were then passed over by the CID aircraft fuselage with major damage to the fuselage. This damage also provided entry points for fuel released from the wing to enter the cargo area of the fuselage.

Close examination of the high speed photography indicates that there was an ignition on the inboard side of the number 3 engine. (See Figure 2.) Unfortunately, no specific identification of this exact ignition location can be seen. However, it is believed that the material that is ignited resulted from the cutter passage through fuel lines carrying degraded antimisting fuel from the degrader, which was located above the engine in the turbo-compressor compartment, down the right side of the engine to the main fuel pump. The engine gear case containing the engine lubricating oil and also a hydraulic pump were also ruptured by this cutter, releasing the fluids in a pressurized, misted form.

Located on the inside of the number 3 engine is the exit port for the acceleration/deceleration bleed. When the engine was struck, it is thought that an engine surge could have been initiated. Under such surge conditions, it is common to have a momentary burst of flame from the bleed port, and this could have been an initiator of the resultant fire. Regardless, with the engine destroyed by the cutter, the release of internal high temperature products of combustion, and the frictional energy of the steel cutter passing through the engine, sufficient ignition potential was present.

Under impact conditions of an engine nacelle with an obstacle, it is normal, through design provisions, to have the engine pod separate from the wing at the pylon fixtures. With the engine being struck at the 38-degree angle on the side, the expected load conditions apparently were not reached, and although the engine was literally broken in half, both fragments remained attached to the wing, providing regions where flame holding action could occur. Again, with the severely yawed condition, a region of recirculation was established between the failed engine and the aircraft fuselage. Fuel from the extensively damaged wing was exiting the wing directly into this recirculation or dead zone. (See Figure 3.) With the aircraft yawed, fuel that

was released into this zone was being pushed, or "squeegeed" along the desert floor by the fuselage, allowing time for the already ignited degraded fuel, oil, and hydraulic fluid to provide a heat source to vaporize the antimisting fuel from its liquid form and subsequently burn. In effect, a chain-type reaction was established as long as the yaw condition continued.

Previous research had provided much data that supported that antimisting fuel could be made to burn and self-sustain in one of two ways. First, if the fuel was sheared at too high a shear rate (or relative air velocity), the resultant droplet condition would burn and propagate, albeit at a rate much slower than normal Jet A kerosene. Some degree of shear and reshear was present in the CID example although it is felt the time exposure to the high heat source was also a major consideration. Secondly, it was known that if antimisting fuel was exposed to a severe, intense, ignition source, this same breakup and burning of the fuel could occur. The ignition source being addressed, in this case, would be illustrated by the sudden rupture of a combustor case, which characteristically releases very high velocity and temperature gases. In the CID, the possibility of such a failure mode definitely existed.

Although most of the preceding is based on analysis from the post-CID examinations of the damage and from the high speed photography, sufficient levels of uncertainty existed that it was felt necessary to reenact this type of a situation for detailed study and analysis.

To achieve this, the Federal Aviation Administration utilized its existing wing spillage facility, with modifications to relate to the CID as it occurred. This facility provides a high volume, high velocity (up to 200 knots if desired) airflow over a simulated wing section from which fuel (at rates up to 300 or 400 gallons per second) can be released, counterflow to the airstream. (See Figure 4.)

The modifications consisted of mounting a fully cowled small jet engine in the discharge airstream, forward of the fuel release port in the simulated wing. (See Figure 5.) The engine that was selected was a surplus J60 engine (the type that powers the JetStar aircraft). Although much smaller than the CID aircraft engines, the operating temperatures and pressures were considered representative. The engine was mounted such that it was canted to the left at 38 degrees. This particular engine also has an acceleration/deceleration bleed exit port that could be examined as an ignition source. Using some scaling factors, the inlet of the J60 engine was located forward of the wing at the same relative position as in the CID situation. The initial plan for this first J60 test was to establish that the flow conditions were similar, or relatable, to the CID case. Subsequent testing would

incorporate the deliberate failure of the engine by stopping its rotation with a heavy steel rod to duplicate the ignition sources.

As is the case in much research, factors that were overlooked in establishing the test procedure prevailed. The first test, which had been to establish whether the bleed port was exposed to the fuel and whether the flow around and behind the engine represented what was seen in the CID, gave an unexpected severe fire. Review of the film and data showed that as the fuel was released at the desired 300 gallon per second rate, it was caught in the boundary flow of the airflow over the cowl, moved forward along the engine case and was ingested by the operating engine. (In all of this testing, the engine was operated on antimisting fuel, so as to not introduce other extraneous factors.) A severe surge developed with fireball exiting both inlet and exhaust. With the fuel continuing to enter the engine, the ignition from repeated surges continued. Note, however, inlet ingestion of fuel did not happen in the CID and was not considered a factor in the J60 testing. Examination of the film revealed that the major portion of burning was in the area downstream of the canted engine. Upstream, the released fuel was exhibiting good antimisting action with no burning. As this unburned fuel flowed around the cowed engine into the recirculation region, it was exposed to the intense heat release area and entered into the burning process.

This initial test, although not as planned, provided sufficient validity to the theory or supposition of what caused the continuous burning in the CID.

Therefore, the second test was to establish whether the absence of the yawed condition would have allowed antimisting fuel to perform as designed in the CID. Accordingly, the engine was then positioned in the same location relative to the fuel release port in the simulated wing, but with no yaw, i.e., the airflow was flowing axially through and along the axis of the engine. The same fuel release rate of 300 gps was used. As in the previous test, an ignition occurred and a fire sustained itself behind the engine. Again, the fuel on the forward end of this region was exhibiting good antimisting action (coarse breakup) and was not burning until it entered the region of high heat release. The subsequent analysis of this test's results indicated that fuel was still being ingested and was providing the ignition source through the engine surges. It was also noted that, although in both the first and second tests the J60 engine flamed out after one or two cycles of surge, the fuel continued to flow into the inlet. With the engine in the 125 to 130-knot airstream, sufficient ram air force was being provided to keep the engine rotating. This rotation was sufficient to continue to shear the fuel entering the inlet and, as it progressed through the

compressor blading, it was being degraded to near Jet A kerosene state.

The third test of this series was designed to evaluate whether the absence of the igniting surge flame would affect the burning action already seen. The engine was positioned further forward than in tests 1 and 2 so that fuel could not be ingested. An ignition source was desired, although, because the intent was to determine if the antimisting action of the fuel was strong enough to cause flame separation. Hence, a small propane torch was located under the exhaust end of the cowled J60 engine to simulate the presence of a surge flame exiting the engine.

The fuel was released at half the rate in the prior tests to minimize the damage that was being done to the facility. After approximately one to two seconds of fuel release, an ignition occurred and continuous burning developed aft of the engine. Analysis eventually led to the conclusion that as fuel was being released, it was being entrained in the exhaust flow field of the engine and was being sheared sufficiently to permit normal Jet A kerosene type of burning. This represented a major problem area that had not been noted or considered in previous work, but it was not considered a factor in the CID because the impact of the cutter ceased engine rotation and no evidence of fuel entering the inlet of the engine occurred.

Test number four was designed to determine if an intermittent ignition source would be able to cause continuous burning of the antimisting fuel as had been seen in tests 1, 2, and 3. The propane torch was replaced with a 2-joule spark ignitor. This was considered the upper bound of severity of frictional sparks that could occur. Conduct of the test at the 150 gps flow rate gave no ignition. This led to a tentative conclusion that either the spark intensity was too small or that intermittent-type ignition sources could not cause ignition of the antimisting fuel. Further investigation of those phenomena are definitely needed.

However, to complete the experimentation begun to evaluate what happened at CID, a final J60 test was conducted. With the engine oriented axially with the airflow, the propane torch was re-installed to cause ignition and burning of the fuel. After this burning was established, a steel rod was driven (using 3-2.75 in. rockets as the propulsive force) down a tube into the engine compressor at a 38-degree angle to cease engine rotation. As had been expected when the case and engine were penetrated, the fire emanating from the engine abated and extinguished, even though fresh fuel was still being provided to the engine through broken lines. These results further supported the hypothesis that the continued burning in the CID was primarily controlled by the amount of yaw.

### CID Relevancy to Past Accidents

With this understanding of the mechanism of what caused the fire at CID, a reanalysis of accidents that occurred in the United States over the time period of 1964 through 1983 was undertaken. These accident data were evaluated using criteria that relied upon the conditions of the CID as it occurred and the CID as it had been planned. Using these as the base criteria, the analysis was further expanded to identify those cases where it was felt antimisting fuel would have or would not have been effective. These four criteria are addressed as follows:

1. CID - As Occurred
  - a. The accident had to be impact-survivable.
  - b. A large fuel release had to have occurred.
  - c. There must have been major damage to an engine without that damaged engine separating from the aircraft.
  - d. Ignition exposure had to have occurred between 100 and 150 knots.
  - e. The aircraft had to be in a yawed condition of 30 degrees or more.
2. CID - As Planned
  - a. The accident had to be impact-survivable.
  - b. A large fuel release had to have occurred between 125 and 155 knots.
  - c. Ignition exposure had to have occurred between 30 and 155 knots.
  - d. The aircraft would have to have been in a minimum yaw or roll attitude at impact.
3. Antimisting Fuel Protection Expected - (ALL of these conditions had to be present.)
  - a. The accident had to have been impact-survivable.
  - b. Fuel release must have occurred at 155 knots or less.
  - c. No major continuous ignition source could have been present at the fuel release location.

4. No Antimisting Fuel Protection Expected - (For this criteria to be in effect, ANY of the following had to be present.)
  - a. The accident was impact non-survivable.
  - b. Fuel release occurred above 155 knots.
  - c. A major continuous ignition source was present at the fuel release location.

Careful consideration of over 100 accidents that involved post-crash fire was given. It was found that only 72 accidents had sufficient data or information to allow application of the four criteria established above.

Of these 72 accidents, first and foremost, no accident was identified as being like the CID as it occurred, thus establishing that this type of scenario is very rare in reality. Twenty-seven accidents were judged to be impact non-survivable and, hence, no antimisting protection would have been provided, or expected.

However, in the 27 accidents, there were no reported fatalities due to fire, although post-crash fire did occur.

In the remaining 45 which were impact-survivable, 347 fatalities due to fire occurred. Only 36 of these 45 accidents met the criteria whereby antimisting fuel protection would have been expected. In these 36 accidents, 345 fatalities were recorded that would not have occurred if antimisting fuel had been onboard. Of these 36, 13 were judged to have been like the CID as planned.

Considering that 347 fire fatalities occurred in all 72 accidents and the conclusion that antimisting fuel could have prevented 345 of them, the case for the use of modified fuels is very strong. (See Figure 6.)

It has been shown to this point that the mechanism of failure of the fuel in the CID case is understood and was duplicated in scale work. It has further been shown that the potential benefit of the use of antimisting fuel is attractive considering the facts of past accidents.

#### Antimisting Fuel Insulating Characteristics

Other positive benefits were seen when the full data of the CID was addressed. Although a very hazardous appearing wave of flame was seen passing back over the aft end of the fuselage,

post-crash still photographs of the fuselage some 90 minutes after the impact (while the cargo hold fires were still burning) showed a skin surface still intact, with some sooting but no fire penetration. Superimposing the view of the fire from the tail camera location on a pre-CID test view from the same camera location revealed that when the initial flame fireball lifted after about 8 to 9 seconds, the only areas of burning were from the cargo hold. Subsequent examination of these regions of the fuselage showed no evidence of fire penetration from outside. All penetrations were the result of fire burning through from inside to out.

To understand and examine this phenomena, scale experimentation was undertaken. (See Figure 7.) This experimentation consisted of providing the capability of initiating and establishing a fire in a 120-knot airstream with standard Jet A kerosene and, once established, having the capability to add Jet A kerosene or antimisting fuel. The fire, or flames thus established were allowed to impinge on a 2-foot square, covered aluminum surface of .040-inch thickness which was instrumented to record its temperature increase. The typical test that was conducted when Jet A kerosene was used resulted in a stabilized flame or fire volume which increased dramatically when the additional kerosene was released into the existing fire. Such tests gave temperature rise information that followed a fairly linear increase from ambient to about 600 degrees Fahrenheit in seconds. (See Figure 8.) When the secondary release was antimisting fuel, this linear increase in temperature was actually reversed and a cooling trend established. (See Figure 9.) In a special series of tests, the initial establishing or flame holding fire fuel source was terminated after the secondary flow started. With Jet A kerosene, the same enlargement of fire occurred; but with antimisting fuel, the fire extinguished while the antimisting fuel was still flowing.

These experiments served to indicate that antimisting fuel, when ignited by either too high a shear rate or by too intense an ignition source, still provides a degree of protection through its slower burning rate. It was postulated that large amounts of liquid were still present in the CID flame and, as it passed over the fuselage, it could not impart high levels of heat transfer to the skin, in essence, until the antimisting fuel reached its boiling point.

Evidence of this phenomena was also seen in earlier experimentation. In the wing spillage testing; in the large-scale crash testing of retired military aircraft; and in the CID; the rate of growth of fireballs was examined. (See Figure 10.) To collect this data, high speed photography was used. For each increment of time, usually one-tenth of a second, the actual two-dimensional area of the resultant fire was

measured (using a planimeter). This area was then converted into a radius term correlating to the equivalent circular area of the flame. The third dimension was ignored since most such flames are symmetrical in that plane.

A comparison of these type of data from the test of crashed aircraft using Jet A shows an initial fireball growth rate of about 150 to 160 feet per second with a continuing growth rate on the order of 45 feet per second growth. Comparing the initial growth rate of the CID fireball gives a correspondingly high value of about 140 feet per second but a rapid decrease to only about 5 feet per second for the majority of the flame life. This initial high rate further supports the information that indicates the initial ignition in CID was of degraded antimisting fuel, oil, and hydraulic fluid. The decreased rate also supports the lower or slower burning rate of the antimisting fuel.

Because in the area of fire research it has been shown to be extremely difficult to model or scale fire, additional experimentation was undertaken to examine this insulating characteristic of antimisting fuel in full scale.

A section of a full-size fuselage was installed at the wing spillage facility. It was instrumented with skin thermocouples both internally and externally. Total heat flux calorimeters were also installed in the face of the fuselage.

This fuselage section was exposed to both Jet A and antimisting fuels. The fuels were ignited using the rocket exhaust to assure ignition. After the antimisting fuel test exposure, the surface of the fuselage, exposed directly to the burning fuel, was again sooted but not penetrated. The effect of recirculation areas was noted on the surface of the fuselage away from the flame. Some small skeletonized areas were experienced on this rear surface. Views from high speed cameras inside the fuselage showed no evidence of front surface penetration for the duration of the 12-second test.

However, the Jet A kerosene test showed extensive skeletonizing of the front surface of the fuselage. Interior views indicate the front surface was penetrated within 2 seconds of fire initiation.

The calorimeter data shows, for the antimisting fuel test, an initial spike of about 20 BTU/ft<sup>2</sup>-sec which appears to be the radiation level of the initial ignition. (See Figure 11.) The heat flux then decreased to the region of 5 to 8 BTU/ft<sup>2</sup>-sec. It appears this lower heat flux is verifying the reduced burning rate and temperature of the antimisting fuel.

The Jet A kerosene calorimeter data shows a much more severe environment. This much higher heat flux is the result of the higher vaporization rate of the Jet A and, hence, the greater radiant heat and heat transfer potential.

### Summary

In summary, the CID was not representative of typical accidents that have occurred in the past. The scenario to which the antimisting fuel was exposed was beyond what the design of the antimisting fuel could withstand. Even so, the antimisting fuel presented a much less hostile environment through its slower vaporization and heat release.

The post-CID investigations to date have given greater insight into the potential, and also the remaining problem areas, for antimisting fuel usage. One such problem that remains that must be examined more closely is the degradation effect when antimisting fuel is entrained in an operating engine's exhaust plume. Such entrainment seems to provide a readily combustible fuel, although no evidence has been seen to suggest upstream propagation to a fuel release point will occur. Even with such possible entrainment and ignition, control of the aircraft attitude to minimize yaw can allow the antimisting fuel benefits to surface. In the case of aft mounted engines, the property of the antimisting fuel that resists forward propagation to the fuel release point (that is, the ruptured wing tanks) can also indicate higher safety.

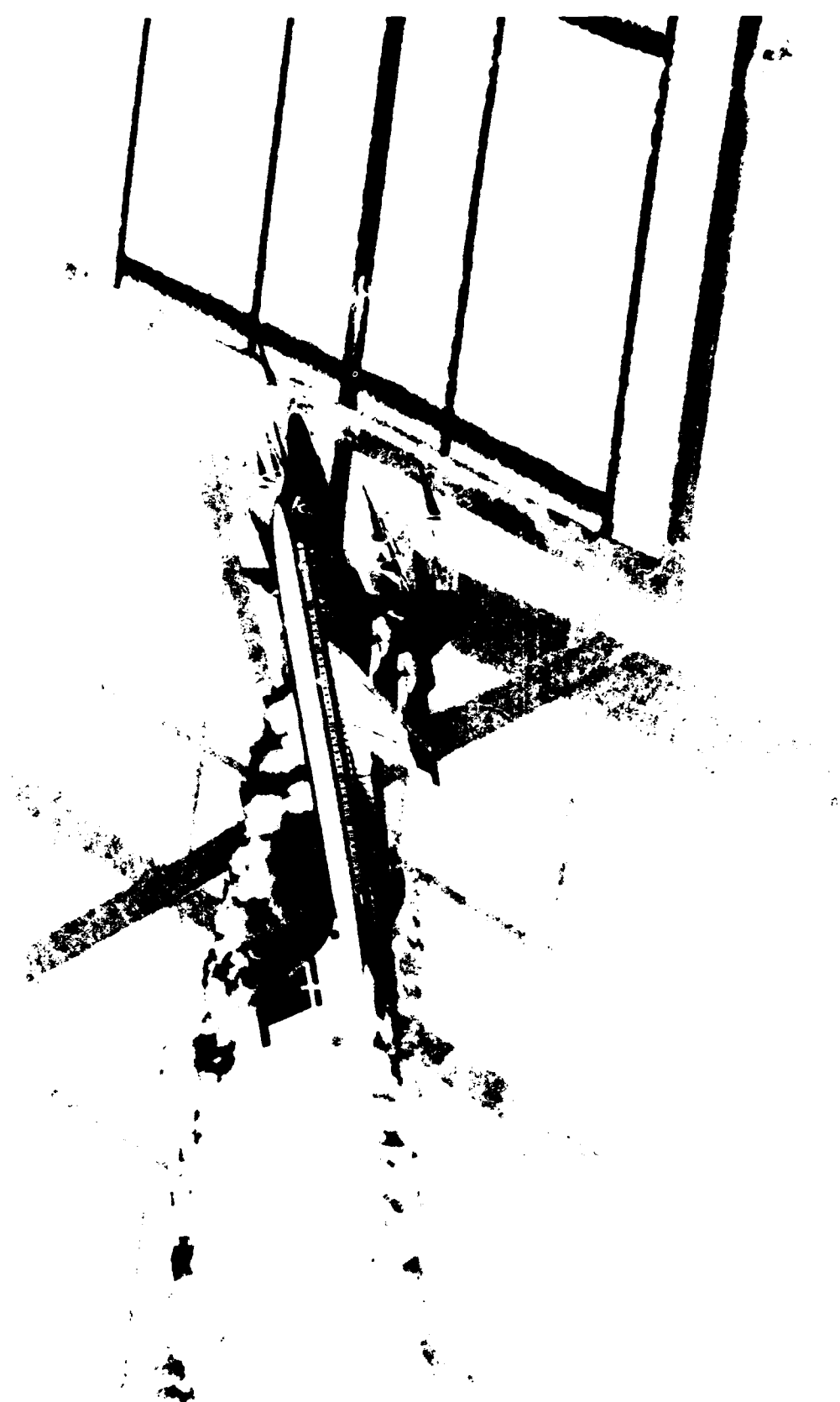


Figure 1. A photograph of the pump assembly used in the experiment.

FIGURE 2 - CLOSEUP OF CUTTER ENTERING RIGHT INBOARD ENGINE NACELLE

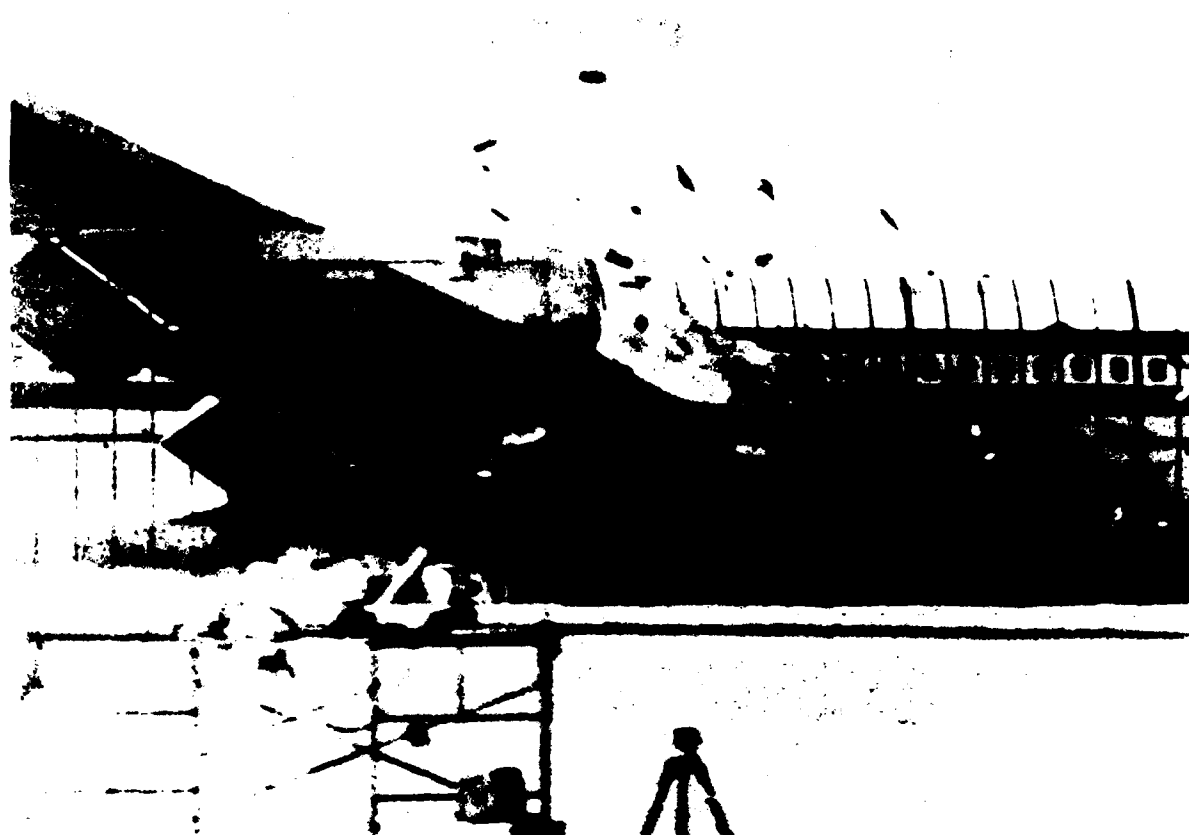
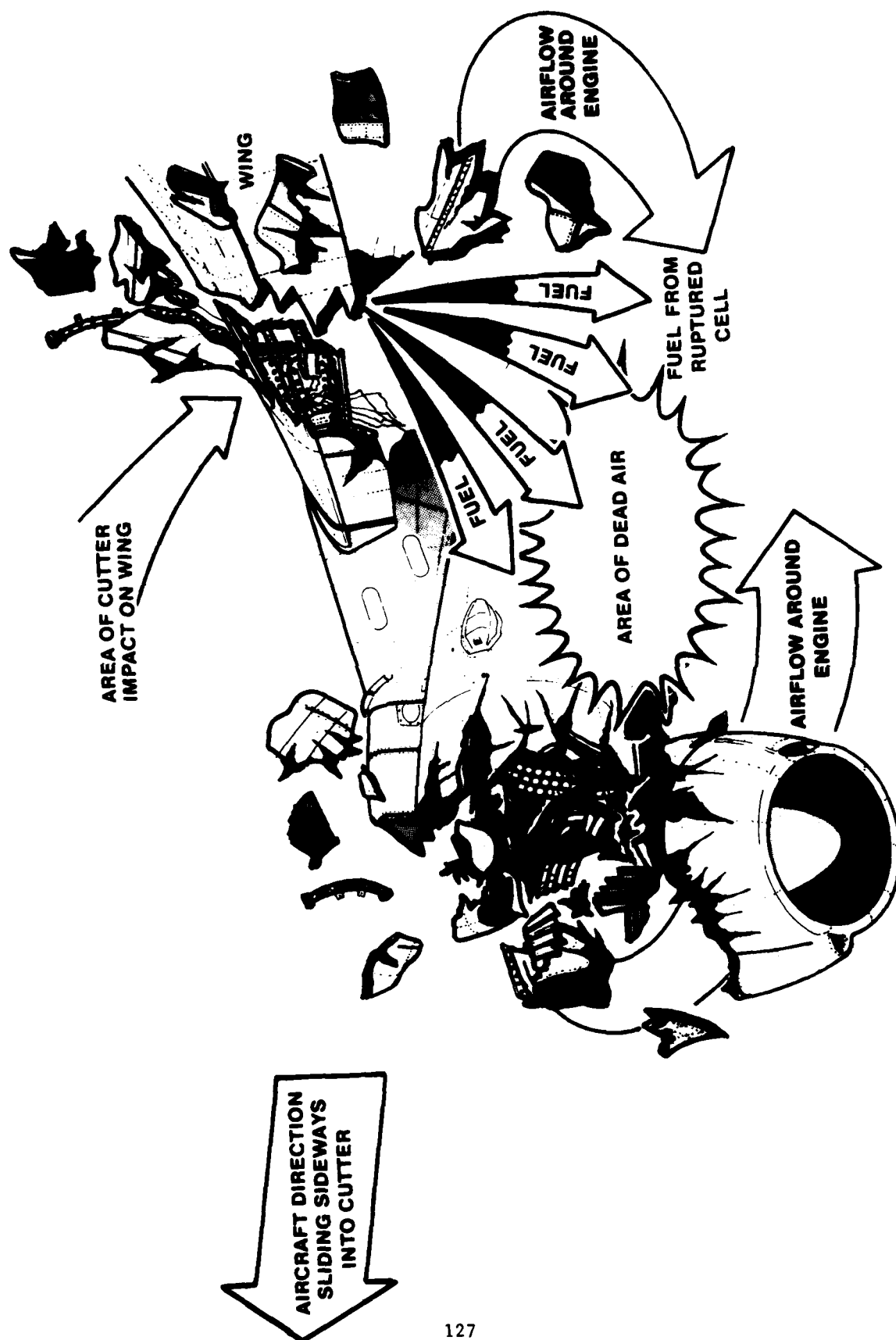


FIGURE 3



ENGINE DAMAGE, FUEL RELEASE, AND AIRFLOW CONDITIONS

# MODIFIED FUEL-WING SPILLAGE TEST FACILITY

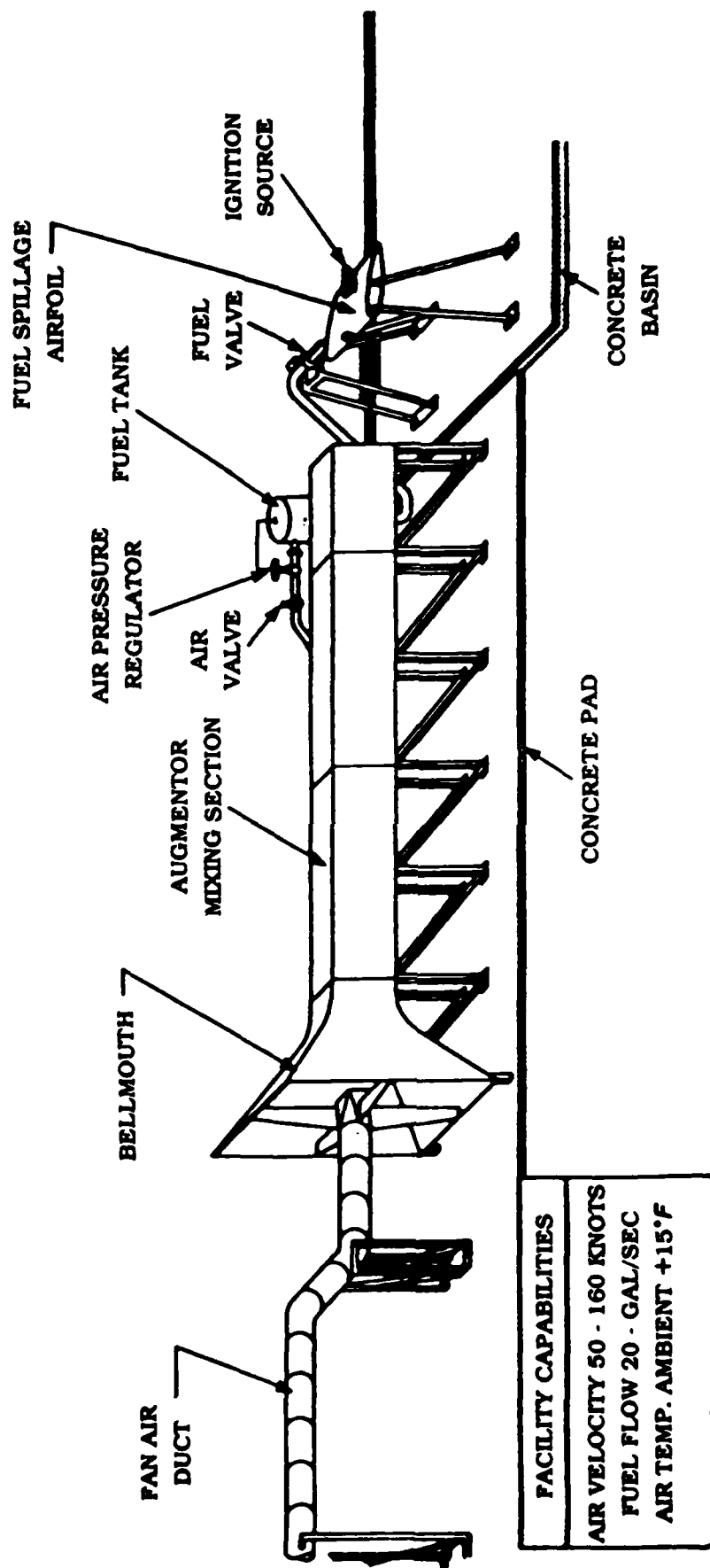


FIGURE 4

FIGURE 5 - COVERED 160 ENGINE MOUNTING  
38° TO THE AIRFLOW DISCHARGE OF THE WING SPILLAGE FACILITY

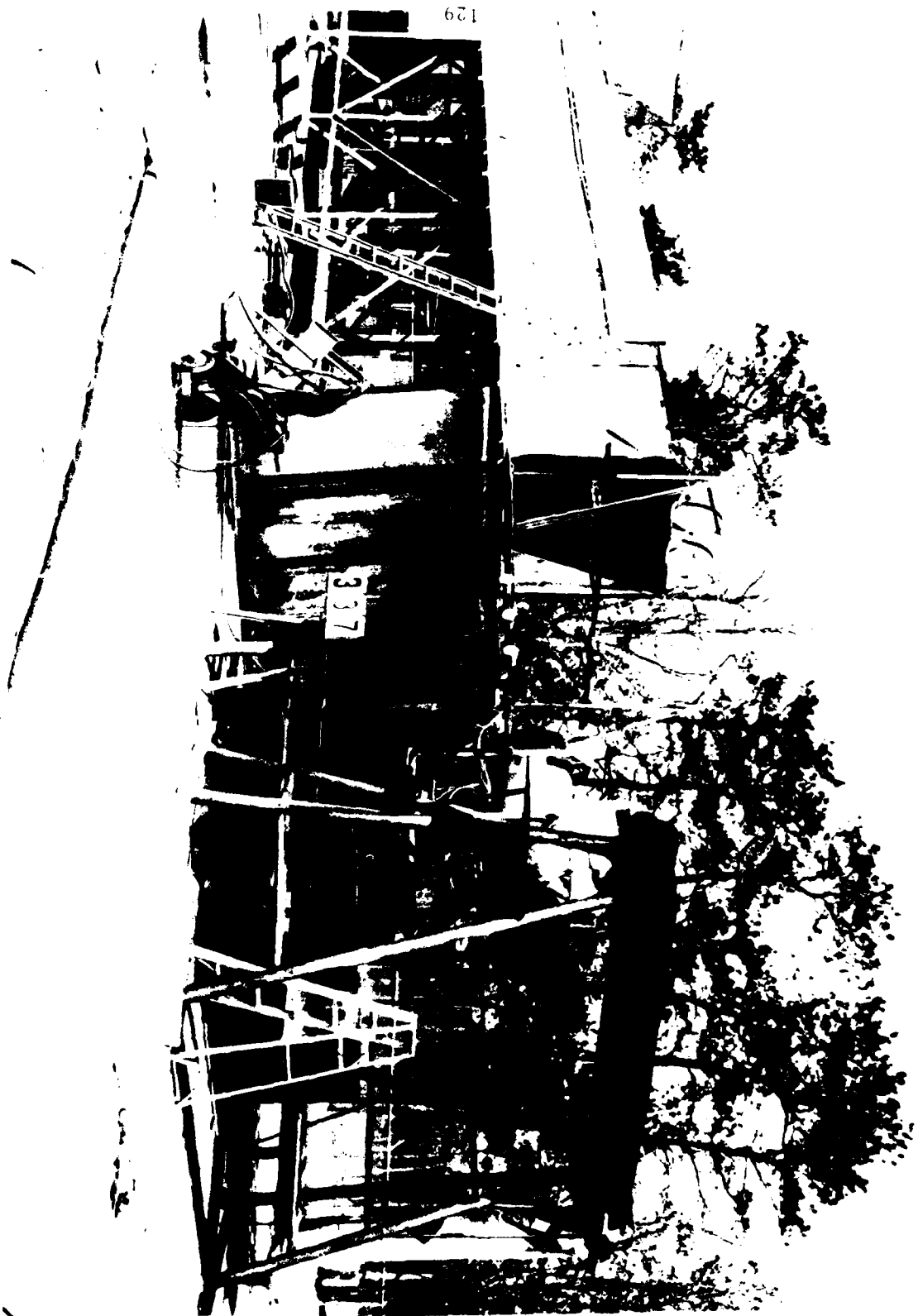


FIGURE 6 - SUMMARY OF POST-CRASH FIRE ACCIDENTS

	<u>FATALITIES</u>		<u>SERIOUS INJURIES</u>		
	<u>Impact</u>	<u>Fire</u>	<u>Unknown</u>	<u>Impact</u>	<u>Fire</u> <u>Unknown</u>
Number of Accidents with Sufficient Data Available for Analysis---72	1227	347	604	170	73 248
Impact Non-survivable No AMK Protection Expected--27	758	0	442	2	0 7
Impact-Survivable---45	469	347	162	168	73 241
Impact-Survivable and AMK Protection Expected---36	469	345	160	157	73 207

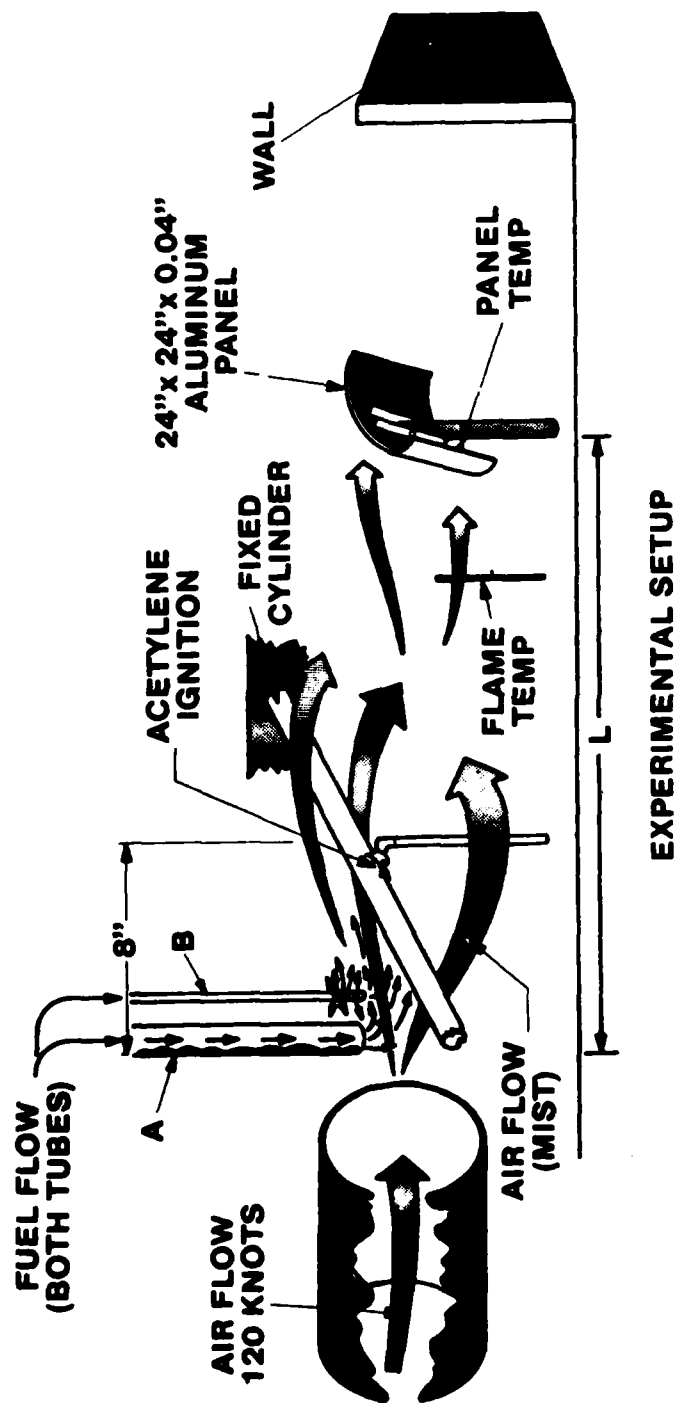
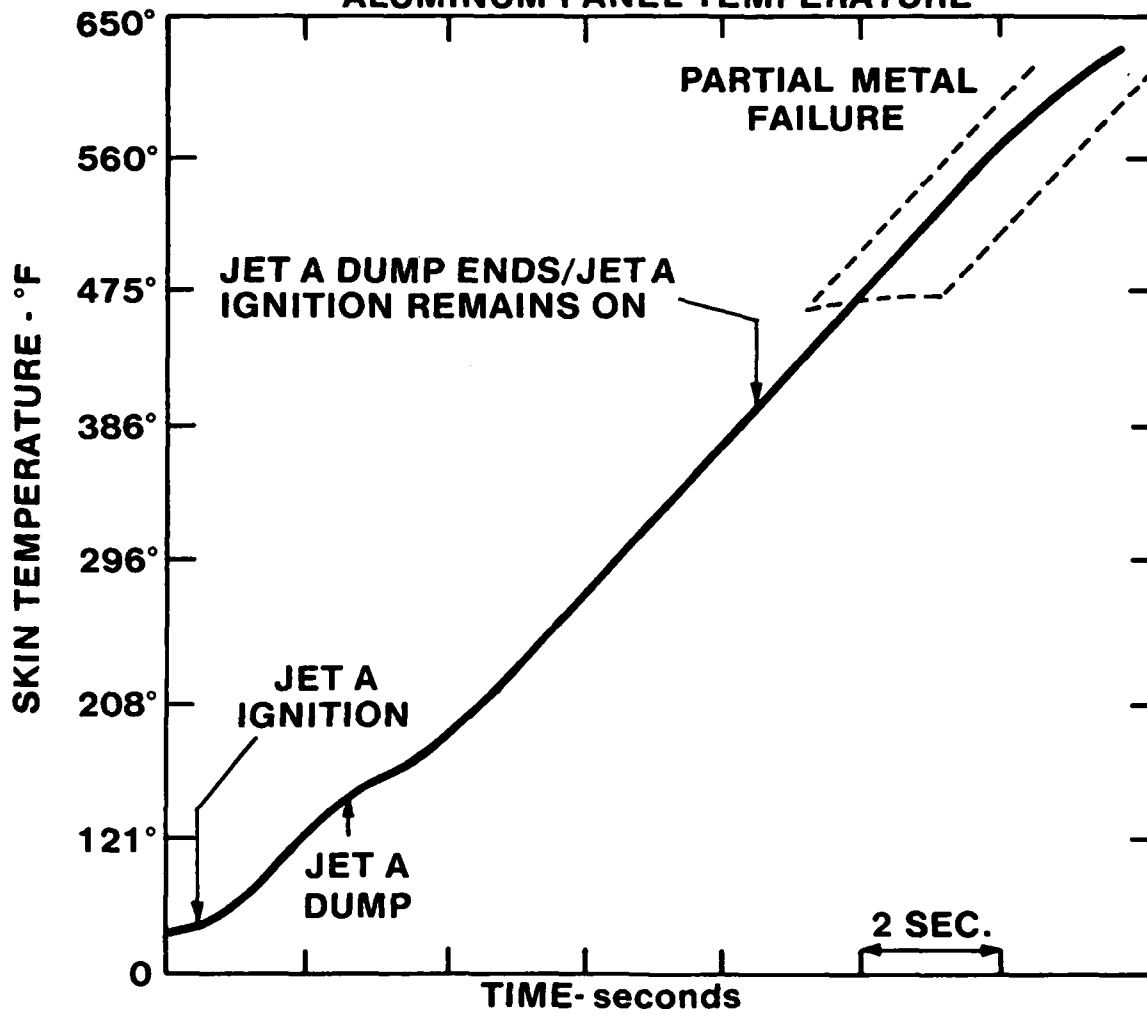
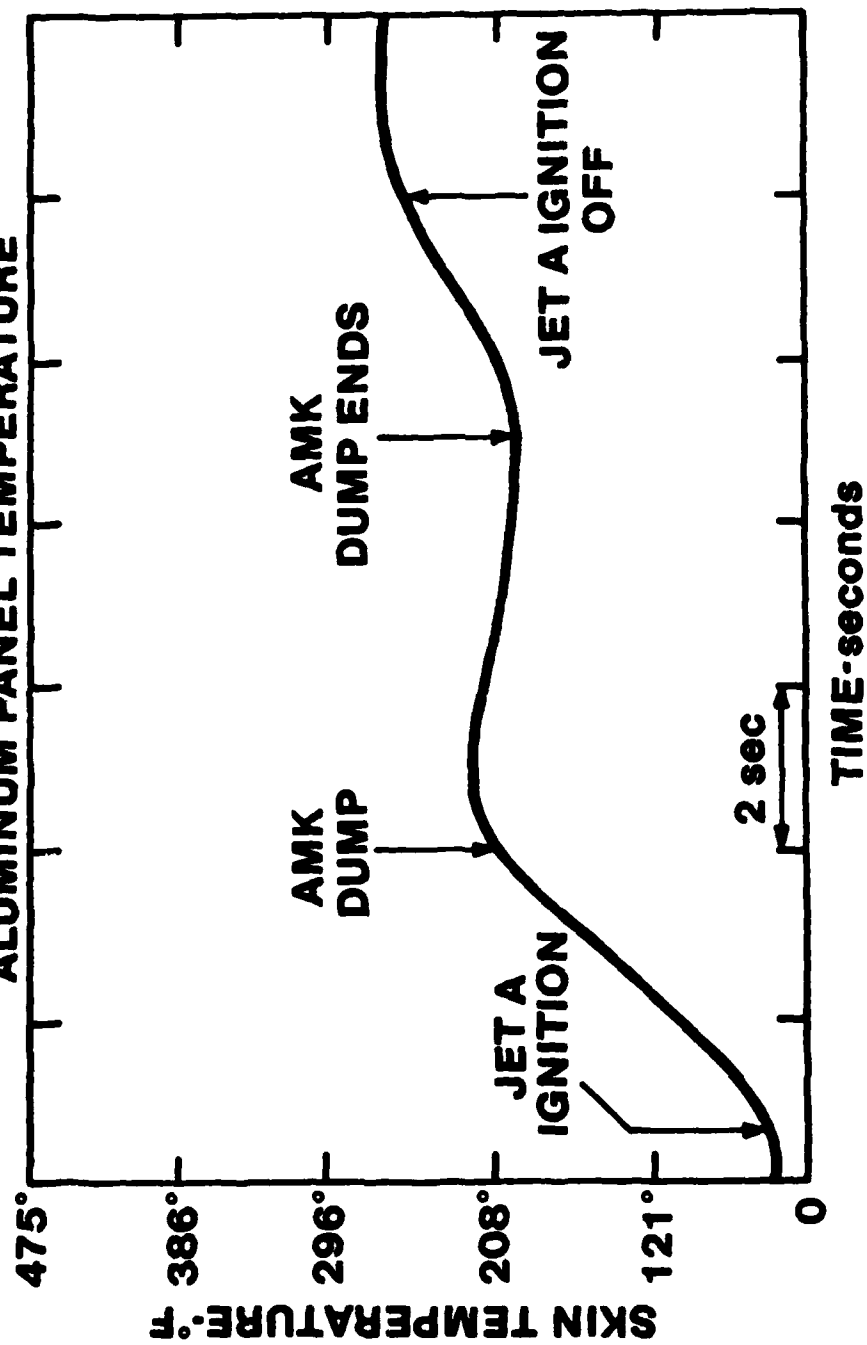


FIGURE 7  
LABORATORY FLAMMABILITY TEST INSTALLATION FOR EVALUATION OF AMK FUEL  
DUMP ON AN ALUMINUM PANEL

FIGURE 8  
EFFECT OF JET A DUMP ON  
ALUMINUM PANEL TEMPERATURE



**FIGURE 9**  
**EFFECT OF AMK DUMP ON**  
**ALUMINUM PANEL TEMPERATURE**



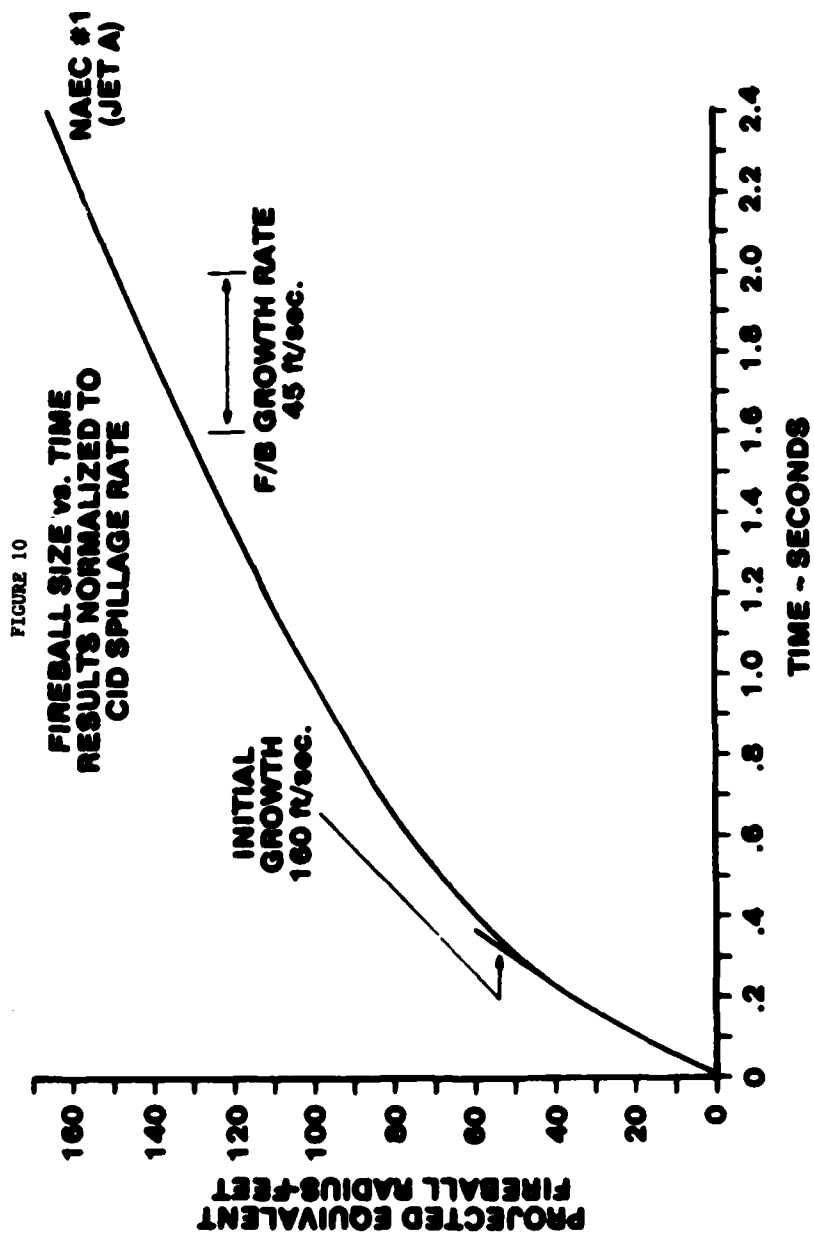
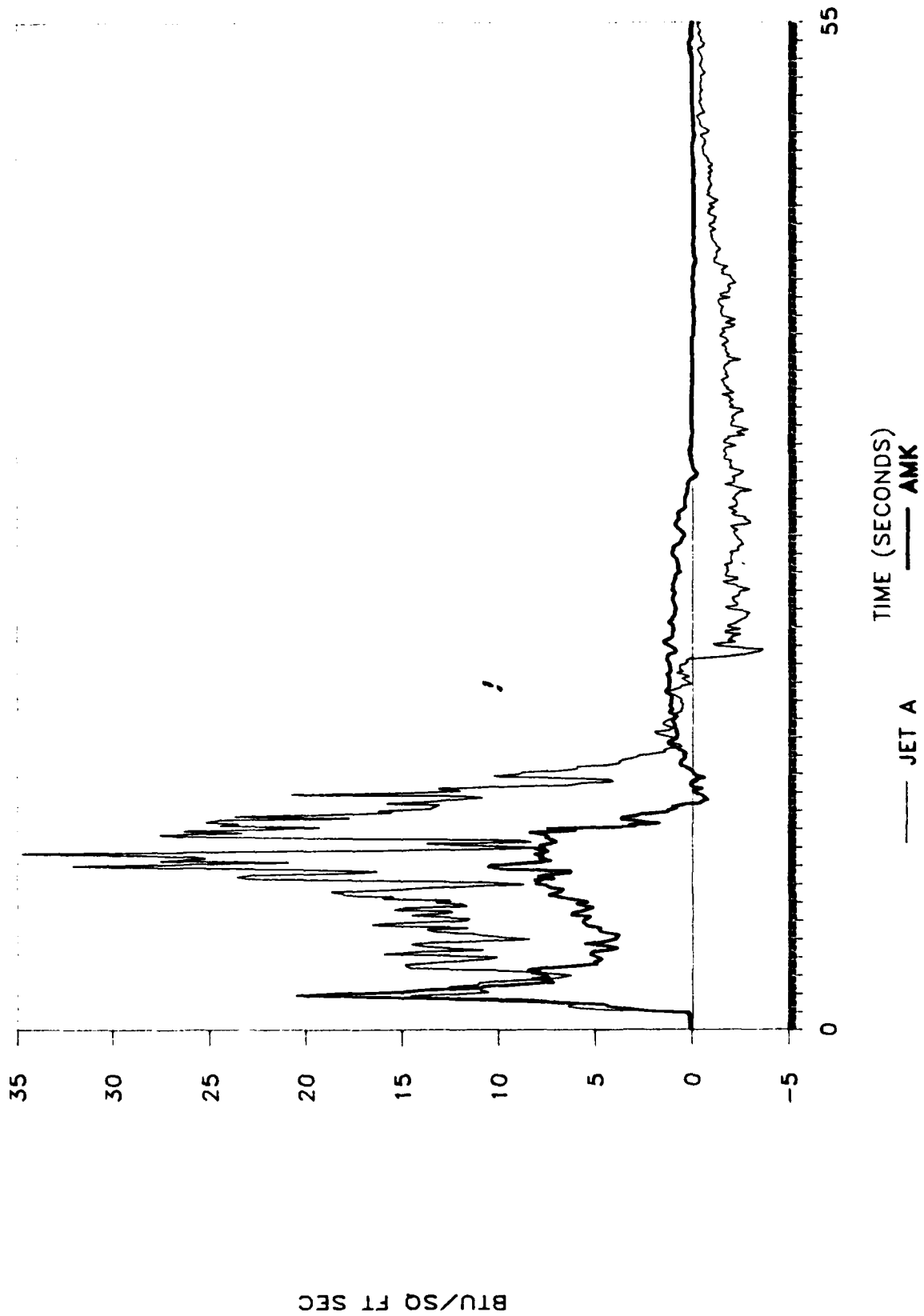


FIGURE 11  
FUEL SPILLAGE ON DASH 7  
FORWARD CALORIMETER



## FAA FUEL CONTAINMENT R&D

by

LAWRENCE M. NERI

The purpose of this presentation is to provide a brief overview of the ongoing and planned FAA fuel containment R&D efforts. The fuel containment program is considered a complimentary approach with the fuel safety program and is an integral element of the overall Aircraft Crashworthiness Technical Program.

This R&D effort has as its primary objective, the reduction of injuries and fatalities of aircraft occupants exposed to post-crash fires in impact survivable accidents (vu-graph 1). Secondary objectives include the identification of systems involved in post-crash fires; assessing the feasibility of transferring existing fuel containment techniques to the various aircraft categories; and the development of crash design requirements for airframe/fuel systems consistent with impact survivable crash scenarios.

The program addresses independently all three categories of aircraft (vu-graph 2). This is primarily due to the different structural configurations and fuel system designs along with the survivable crash impact environment associated with these aircraft categories. The question always raised concerning R&D efforts is: Why are you doing this program? The answer is easy, accident statistics. How can we effectively reduce occupant injuries and fatalities in an survivable crash impact?

Vu-graph 3 illustrates a compilation of accident data generated independently by three major fixed-wing transport airplane manufacturers (Boeing, Lockheed and

McDonnell Douglas) under a FAA/NASA sponsored project. The objective of these FAA/NASA studies was to: 1) develop transport crash scenarios based on impact survivable accidents; 2) identify systems or subsystems which contributed to occupant injuries and fatalities; 3) define R&D areas; and 4) identify test techniques and methodologies needed to evaluate the crash dynamic response of transport airplanes. The criteria used to select the accidents to be evaluated were: 1) airframe survivable volume was maintained during impact; 2) at least one survivor; 3) potential for egress was present; and 4) the accident demonstrated structural or system (fuel, etc.) performance. An analysis by FAA Technical Center personnel of the 176 accidents which collectively were found to meet the criteria established in the FAA/NASA contract produced the following information.

Vu-graph 4 illustrates accident percentage (176 total accidents) versus major failure modes. It can be seen that tank rupture was present in 44 percent of the domestic accidents and 68 percent of the foreign accidents while engine separation occurred in 49 percent of the domestic and 46 percent of the foreign accidents.

Vu-graph 5 presents accident percentage versus fire and fatalities. This slide shows that 41 percent of the domestic accidents and 72 percent of the foreign accidents experienced post-crash fires. It also points out, that 26 percent of the domestic accidents had post-crash fire and fatalities, while 45 percent of the foreign accidents had post-crash fire and fatalities.

Perhaps the most significant output of this analysis was the development of the sequence of events between the structure related event failures and subsequent fire and/or trauma fatalities (vu-graph 6). The sequences which lead to fire fatalities are highlighted.

Vu-graph 7 presents those impact events which possess the highest fuel spill potential. While vu-graphs 3 through 7 have presented data relative to turbine powered transport airplanes, this type of data has been generated for rotorcraft and is being generated for general aviation airplanes.

Vu-graph 8 presents the generic technical approach addressing fuel containment R&D for all types of aircraft. The first three steps are in various stages of completion while the remaining four address both recently initiated and planned efforts.

Vu-graph 9 illustrates in a flow diagram format, the sequence of events and principal elements which will lead to the design criteria required to satisfy the primary objectives of this R&D program--that is the reduction of injuries and fatalities to occupants exposed to fire in impact survivable accidents. While this vu-graph depicts transport airplanes, it can be considered as a generic approach.

FUEL CONTAINMENT R&D PROGRAM

OBJECTIVE

- REDUCE FATALITIES/INJURIES IN IMPACT SURVIVABLE ACCIDENT BY MINIMIZING  
THE POST-IMPACT FIRE HAZARD

VU-GRAPH 1

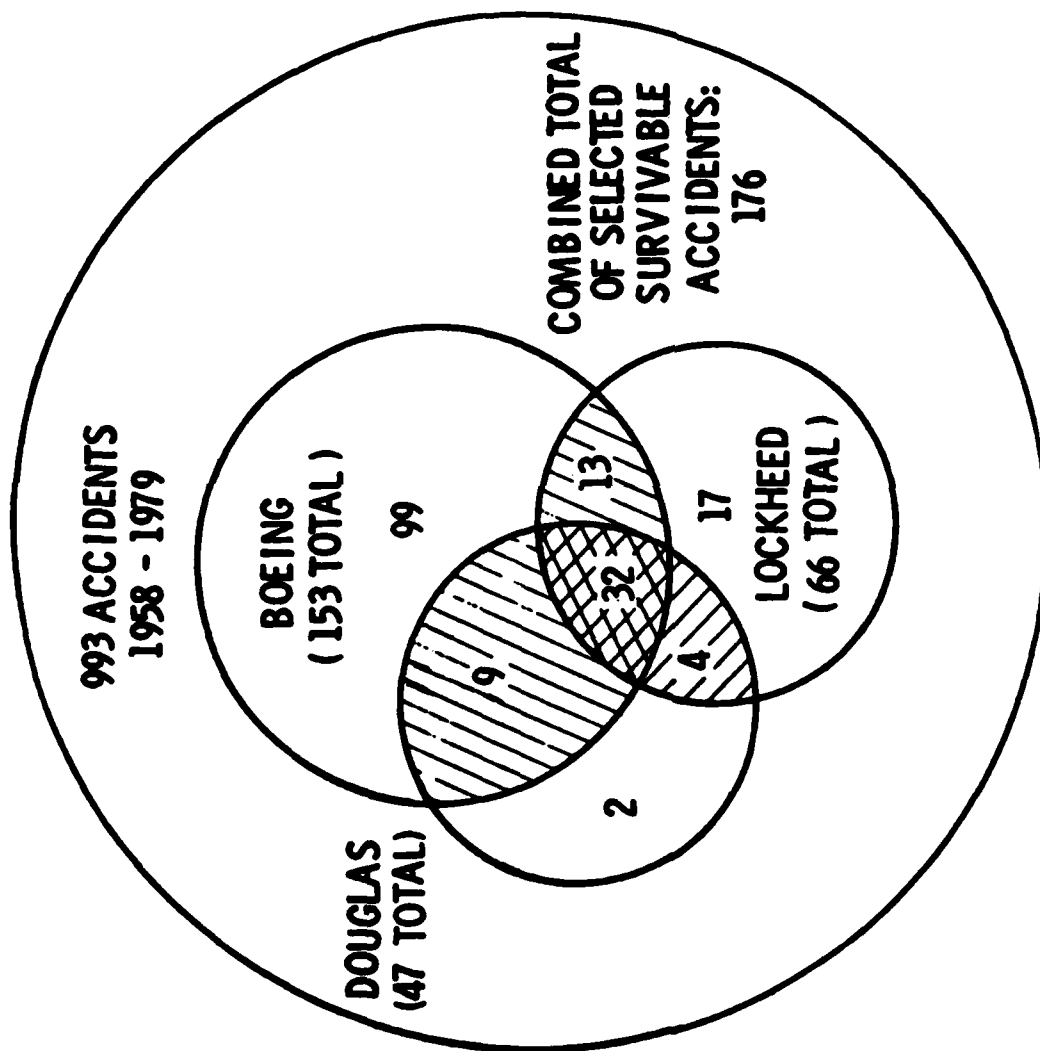
## FUEL CONTAINMENT R&D PROGRAM

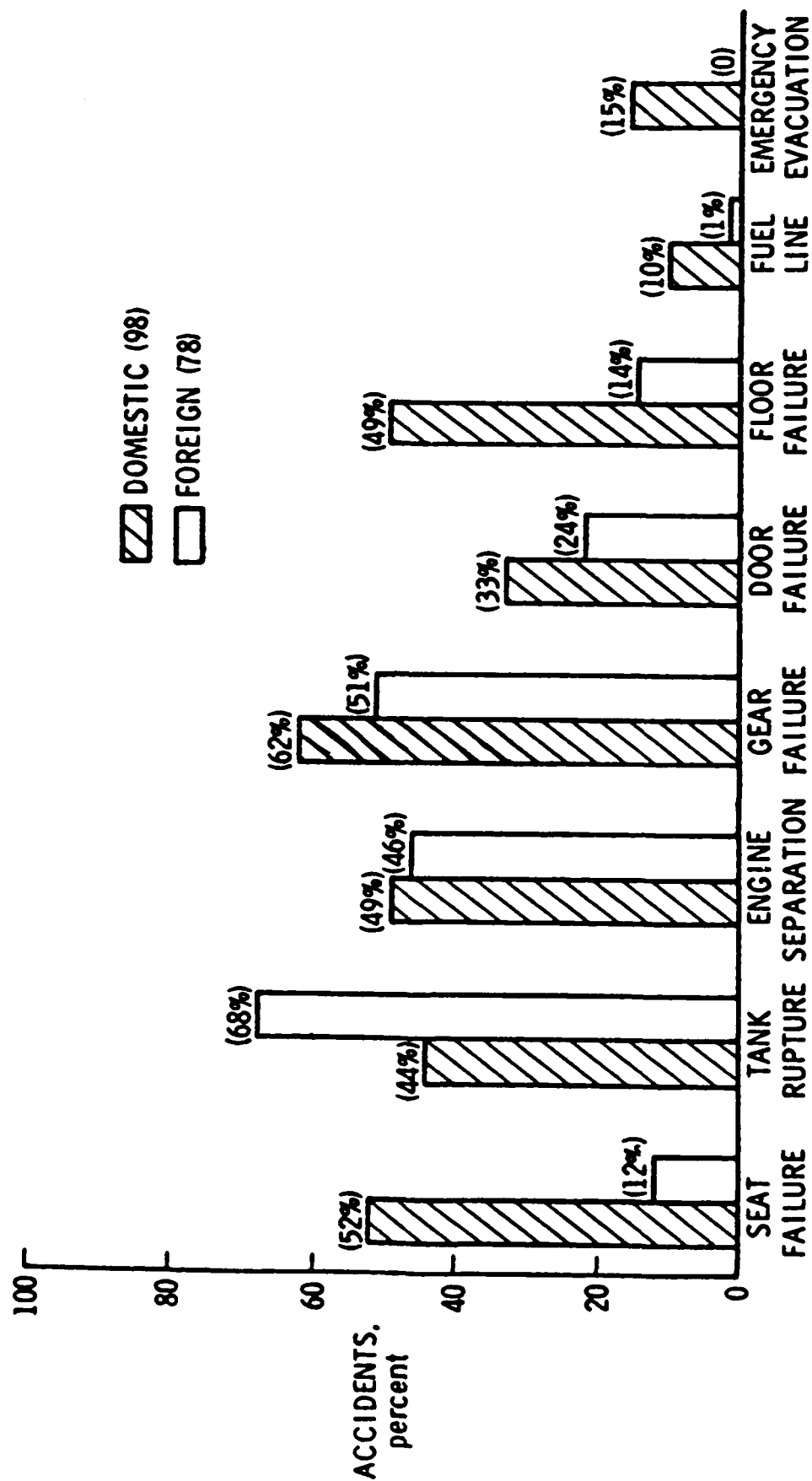
### SCOPE

- |                     |                                     |
|---------------------|-------------------------------------|
| . FAA PART 25       | TRANSPORT AIRPLANES                 |
| . FAR PARTS 27 & 29 | ROTORCRAFT (NORMAL & TRANSPORT)     |
| . FAR PART 23       | GENERAL AVIATION AIRPLANES (NORMAL) |

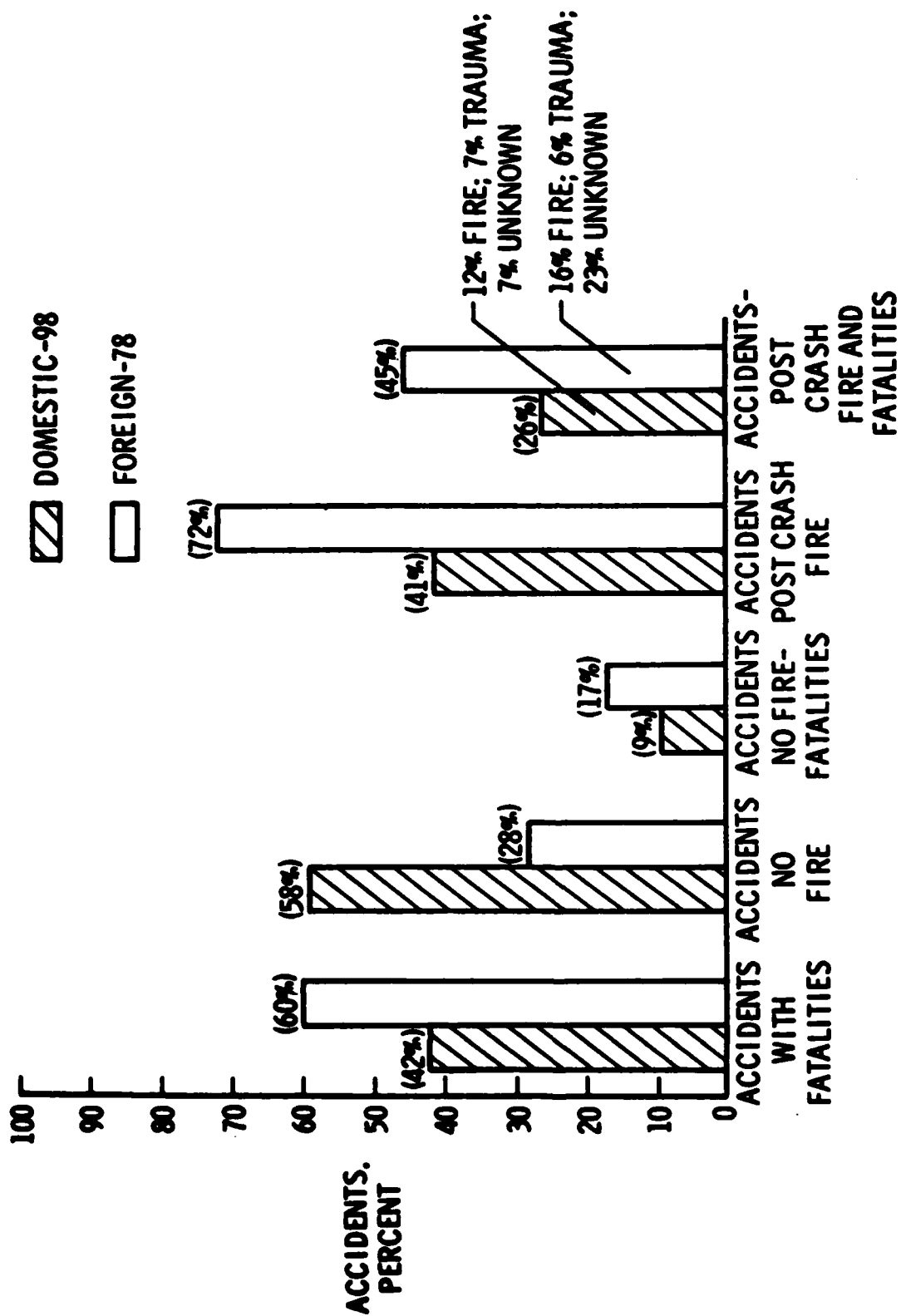
### DIFFERENCES

- DESIGN REQUIREMENTS (STRUCTURAL/FUEL)
- CRASH IMPACT ENVIRONMENTS





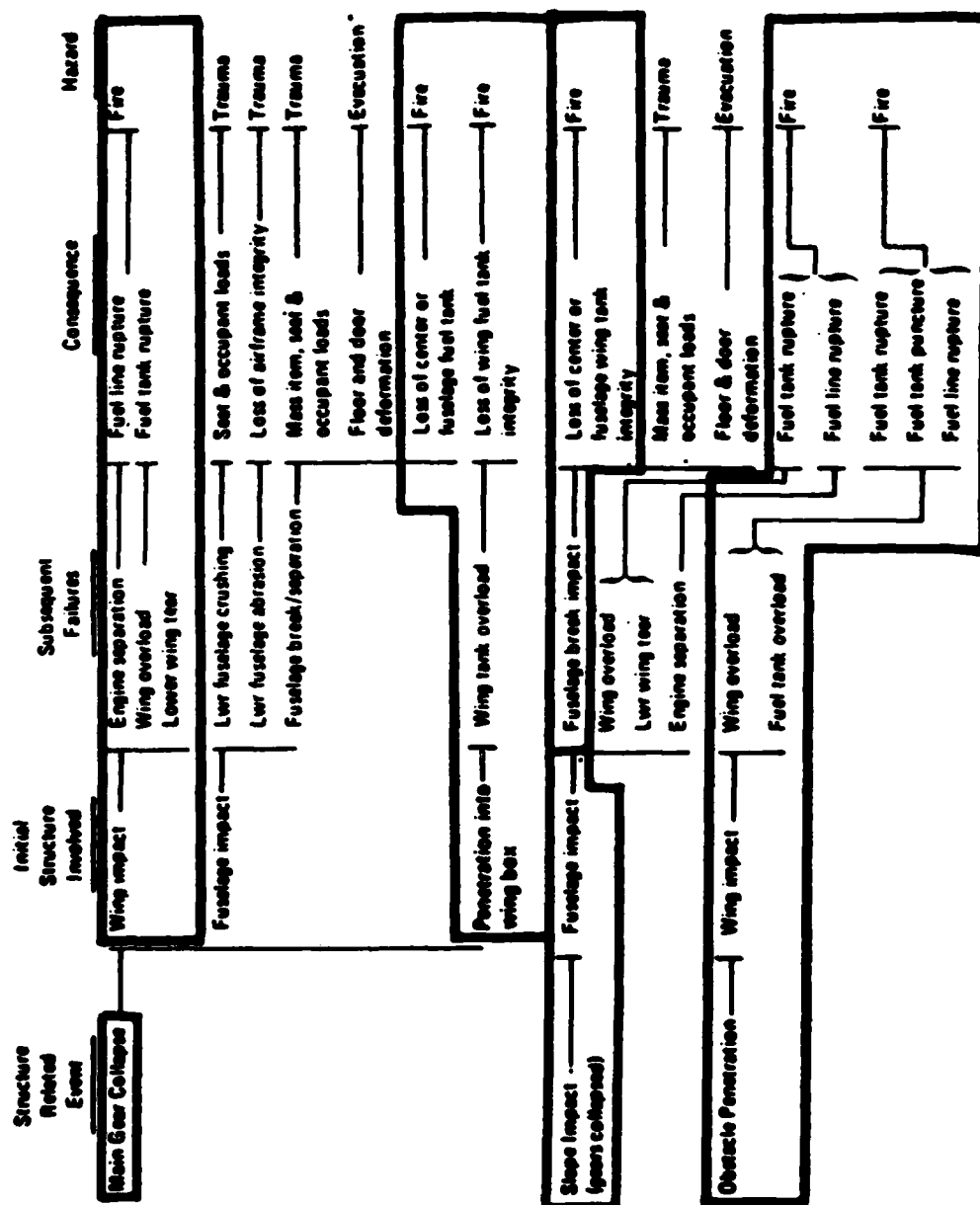
(A) - FAILURE MODE (PERCENT OCCURRENCE)



(B) - ACCIDENTS WITH FIRE AND FATALITIES

# ACCIDENT DATA SHOWS:

## RELATIONSHIP BETWEEN STRUCTURE RELATED EVENT, FAILURES, FIRE HAZARD CONSEQUENCE FOR CRASH SCENARIO



## **FUEL SPILLAGE POTENTIAL**

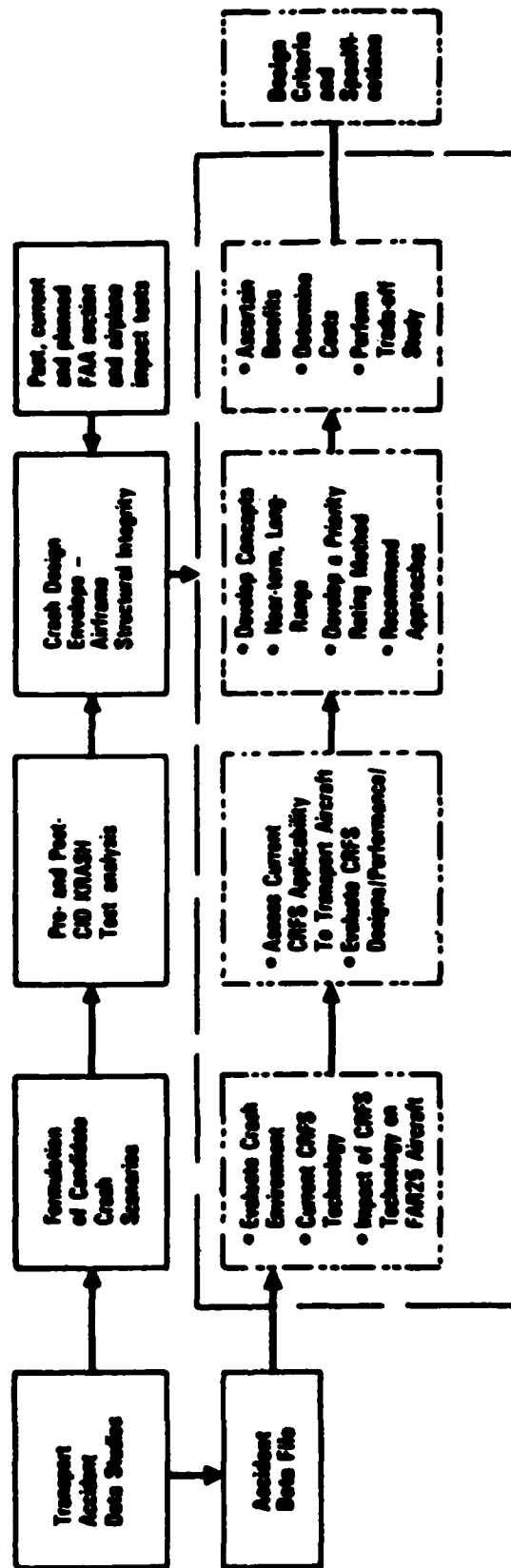
- **CONCENTRATED IMPACT LOADS**
  - TREES, POLES
- **LOCAL PUNCTURE**
  - ENGINE
  - LANDING GEARS
- **DISTRIBUTED IMPACT LOADING**
  - WING TIP GROUND CONTACT
  - FUSELAGE IMPACT
  - PLOWING
  - CRUSHING
- **INTERNAL PRESSURES**
  - INERTIAL LOADING
  - FUEL SLOSH

## FUEL CONTAINMENT R&D PROGRAM

### APPROACH

- REVIEW CRASHWORTHINESS DATA AND PUBLICATIONS
  - SAFER - FAA
  - MILITARY - INDUSTRY
- ESTABLISH CRASH ENVIRONMENT
- IDENTIFY INJURY/FATALITY RELATIONS WITH FAILURE MODES
- RELATE CURRENT FUEL CONTAINMENT TECHNOLOGY/HARDWARE TO VARIOUS AIRCRAFT TYPES
- EVALUATE/RATE LEVELS OF PROTECTION ASSOCIATED WITH OVERALL SYSTEM AND VARIOUS COMPONENTS FOR EACH AIRCRAFT APPLICATION
- CONDUCT TESTING (AS REQUIRED)
- GENERATE COST-EFFECTIVENESS DATA ASSOCIATED WITH PRACTICABILITY OF DESIGN CRITERIA

# RELATIONSHIP BETWEEN CURRENT "FUEL CONTAINMENT" AND ONGOING FAA RESEARCH



VU-GRAPH 9

LUNCHEON GUEST SPEAKER:

Mr. John Enders

FEDERAL AVIATION ADMINISTRATION  
FUEL SAFETY RESEARCH WORKSHOP  
Ramada Inn, Seminary Road  
Alexandria, VA  
October 29-November 1, 1985

"PRESERVING SAFETY IN A HOSTILE ENVIRONMENT"

by

John H. Enders, President  
Flight Safety Foundation  
Arlington, VA

Mr. Chairman, Distinguished Guests, Friends and Participants in this most important conference. It is a pleasure and privilege for me to be with old friends and colleagues again. Even though I am no longer a practicing engineer, I feel a special kinship with this group, having worked with many of you over the past years.

Curiously, my first job as a junior engineer-in-training at NACA's Lewis Flight Propulsion Laboratory was concerned with understanding combustion processes in jet and rocket engine combustion chambers. After 30 years of wandering through an aviation career, my last tasks at NASA involved managing large scale aircraft fire research efforts. I guess it could be described as a matter of "out of the frying pan and into the fire!"

I thought that it would be perhaps of some value to share a perspective on the matter of aircraft fire with you today, having personally observed and participated in over 3 decades of effort to control it. Then I will close with a few observations about the overall aviation environment we have today.

Certainly, fire is not the most serious killer...cancer, motorcycles, automobiles, drugs, and other hazards take more lives annually than does fire. Some 8,000 fire deaths occur every year in the U.S., with perhaps 30-40 per year average in air carrier accidents attributed to fire and its effects. Recently, that estimate was questioned and suggested to be about 150 per year. But even at the current unrealistically high insurance compensation levels of \$600-700,000 per death in air carrier accidents in the U.S., economic arguments alone are not compelling in focusing our attention so sharply on aircraft fire.

Why does fire hold such fear and fascination for us? There is something primitive or primal about fire. Perhaps our fear or respect has its origins in a genetic code that has been passed down from that far distant dim past when our prehistoric ancestors first encountered fire. The Ancients regarded 4 elements as fundamental--Earth, Wind, Water and Fire. Both revered and feared, fire remains both friend and threat in our time. Man's efforts to control it to our benefit over the years has yielded considerable frustration and frequent pain. Indeed, our understanding of it is far short of total. Today, we continue to battle fire ignorance, even out of logical proportion to other hazards to mankind. Perhaps we feel a moral imperative, as Olly St. John of the U.K. CAA

once said, to work on those things where technology promises preservation of life.

A look at the history of aircraft fire can be instructive and interesting. Contrary to what the critics would have us believe, aircraft fire has been a focus of research enquiry and engineering and regulatory improvements since the beginning of flight. Jerry Lederer informs me that the Wright Brothers incorporated a lanyard ignition cut-off on their early airplanes that could be activated in the event of a crash. A search of the aviation literature shows that in 1919, NACA published a two-volume translation of a French report: "On the Problem of Fire in Aircraft," dealing mainly with in-flight fires. Other representative milestones:

- |           |   |
|-----------|---|
| 1926      | U.S. Army Air Corps conducted engine fire tests at McCook Field, Dayton, Ohio.  |
| 1930's    | Various fundamental studies of aircraft fuel & fire by government, industry and academia.   |
| 1940-50's | The NACA Lewis Full-Scale Aircraft Crash Test Program that established a comprehensive engineering basis for the origin and mechanism of aircraft crash fires, and explored means of fire suppression.  |
| 1950's    | Establishment of the U.S. CAA Engine Fire Research Facility at Indianapolis; later moved to Atlantic City.  |
| 1960's    | Continuation of full-scale crash tests by Flight Safety Foundation's AvSER Division under contract to U.S. Army and FAA.<br><br>NASA/USAF/Industry research on lightning-induced fuel fires.<br><br>U.S. Army experiments with gelled and emulsified fuels.<br><br>FAA tests with anti-misting additives.<br><br>Industry IRAD fuel system design improvements.<br><br>FSF development (Army Contract) of helicopter crash-resistant fuel system with subsequent Army implementation in UH-1 helicopters. |
| 1970's    | Sophistication...computer/pro-active chemistry at work by RAE, NASA, FAA, USAF, French and German government and industry.<br><br>U.K.'s CAA representative Laurie Edwards first coined the "AMK" term during a CAA-FAA-NASA anti-misting fuels meeting in Washington.<br><br>NASA's FIREMEN program established basis for improvements in materials flammability through contracts with industry and academia.   |

FAA tests on cabin fires at NAFEC and complementary tests by industry established the environmental and materials flammability data base.

FAA's SAFER Committee, composed of an international group of representatives from government, industry, airlines, universities and consumer groups, examined the state of aircraft crash fires and fuel containment knowledge at the end of the 1970's decade, producing a comprehensive status report of what was feasible for design and operation implementation, what regulations were feasible, and identified further work needed to continue the improvement of the aircraft fire safety record.

1980's      FAA/NASA full-scale crash impact demonstration of instrumented B-720, gathering data on virtually all aspects of crash dynamics and fire that had been researched to date in smaller scale tests.

The stimulus for all of this activity was, of course, accidents and serious incidents, as well as self-preservation interests of the growing air carrier industry that had to operate safely in the public eye. In addition, public confidence required assurance of safety through federal certification and inspection. While federal rulemaking has often lagged industry practice and capability, the FARs and their equivalents elsewhere are steadily being improved as our increasing understanding of fire and fuel behaviour permits. Perhaps this process should be simplified and accelerated.

The elusiveness of solutions to this immensely complex problem is frustrating. How many good ideas have failed the test in laboratory or application? The range of variables at work in an aircraft fuel fire is nearly unbounded. Consider the requirements we face in aviation: carrying large amounts and high pumping rates of combustible fuel in strong but lightweight tanks in relatively close proximity of upwards of 400 people through continually varying temperature and pressure regimes and acceleration, temperature cycling and fatigue environments that in rare instances become structurally destructive. Integrity of the fuel containment system is then threatened, and unplanned ignition sources can start the fire. If the fire occurs while in flight, the aerodynamics of the situation make the management of that fire tough enough, and engine integrity assurance makes not only design, but also maintenance, important considerations as the engine and related fuel system age. If the fire occurs on the ground in a crash situation, the variables are nearly infinite and become less predictable. For instance, as the intensity and stoichiometry of an open fire vary, the chemical by-products also change, making effective solutions much more broad-based and more difficult.

It should be noted here that in the case of the AMK tests, somehow the impression was created within the public mind that it offered a panacea to post crash fire. Throughout the development of knowledge about crash fires, it has been recognized by those involved that the linkage of ignition and fuel through the mist cloud by a travelling flame front is only one of many elements that determine the development of an aircraft fire...elements that have to be dealt

with in an integrated manner if the fire is to be controlled. AMK, in the absence of other supporting measures, cannot be expected to do the entire job of controlling a post crash fire.

How can we get an engineering handle on preventing or minimizing the fire? It requires mixtures of engineering, science, mathematical, chemical, biological and other disciplines. These disciplines must operate on innovative ideas that can flourish only in an openly cooperative teamwork environment between government agencies, airlines, manufacturers and other private sector groups. The tough problems that aircraft fuel fires pose will yield only to integrated, cooperative efforts. Indeed, every substantive advance has been the result of the efforts of not one government agency or one university laboratory or one private company, but of a well-managed integrated team of people with different individual motivations and skills as well as the shared goal of increased safety.

Technical solutions have to be economically realistic and their implementation will depend upon the effectiveness and safety commitment of top management in government, manufacturer and airline industry organizations. Each must be equal partners in the process and each must be technically and managerially competent to deal with the others. The late Frank Kolk, former Vice President-Development Engineering of American Airlines, described this partnership in safety as a three-legged stool...the three legs being government, manufacturers and airlines. To be stable, the stool must be supported equally by each of the three legs; if one is shorter or weaker than the others, the stool still cannot be supported.

The stress of economic problems of the past five years, the attempts to balance the federal budget and the insidious effects of deregulatory actions have unleashed forces within the aviation community that have undermined the stability of this three-legged stool. Another insidious factor at work is the absurdly high accident litigation settlements increasing the cost of doing business, while at the other end of the process are forces promising the passenger equally absurdly low ticket pricing. Mr. C. E. Calas, Director-General of the Finnish National Board of Aviation, noted recently during the FSF Cold Weather Operations Workshop in Helsinki that aviation safety cannot flourish in bad economic times.

It has been demonstrated time and again that technical innovation is based on fundamental work begun 8-10 years prior to implementation. Thus, we are employing technologies in fuel safety today that were conceived and nurtured in research efforts in the early 1970's. Continuity in operating problems research must be maintained, for operating problems never go away...they have a vicious way of biting one whenever one's effort flags. Civil aviation research and development flourished during the decades of the 50's, 60's and 70's. Now we see investment in civil aviation sharply reduced in both the private and public sectors. Recommendations have been made to federal budgeteers that private industry can alone take care of civil aviation research. This is undoubtedly an appealing argument to economists, but experience shows that nothing could be further from the truth than this assertion, and, if we want to get our aviation safety house in order and make certain that we have the wherewithal to continue

safety improvement in the years ahead, we must work to restore the competent balance of the three-legged stool. Economists might benefit from an equivalent of a three-legged stool by dealing directly with operational and practical management types when they formulate their recommendations and decisions. There is a disturbing naivete at work today that will continue to give us problems if we do not overcome it.

Paul Johnston, in his 1985 William Littlewood Memorial lecture, pointed out very clearly the dangers of shrinking the airline development engineering staffs. Faced with the economic survival decisions brought about by recession and sharp competition from deregulation, many airline managements have had no choice but to reduce expenditures in the rear lines, while continuing the vital front line functions of operations and maintenance.

There went one leg of the stool.

At the same time, federal budget balancing decisions, while a desirable goal, nevertheless allowed attrition of not only government civil aviation research budgets, but also, perhaps more importantly, the attrition of inspection staffs and research staffs and, with them, the loss of valuable experience depth, especially in safety and operational problems engineering areas.

There went the second leg.

This leaves the bulk of the burden on the remaining leg: the manufacturers, which is neither fair nor wise. Manufacturers do not operate public carrier aircraft to tight schedules, nor do they inspect the operations and maintenance of the air carriers. They need the interaction with the other two groups for their team contribution to be effective over the long term.

Communication of safety information is absolutely vital to rapid progress in safety improvement, and it too has fallen victim to the pressures of economics. Staff shortages and travel fund restrictions have sharply reduced the opportunities for valuable and productive face-to-face interchanges between research and development specialists, where creativity stimulated by professional argument is so vital to the continued control of operational safety.

Other factors that have adversely affected the necessary intergroup communication within the aviation community are the excesses of product liability and the sharp economic competition brought about by deregulation. As imperfect as it has always been, communication is far more crippled now than it was a decade ago.

Lest I leave the wrong impression, I want to make clear that economic deregulation, per se, is not totally undesirable to the extent that other conditions--most importantly, public well being--permit. However, public well-being, I submit, is more than a low ticket price. We deal with most perishable commodities, people and time, and perhaps the concepts of deregulation were applied with a disproportionate concern for marketplace economics without due regard to the many unforeseen secondary effects.

In summary, we can see that the problem of aircraft fire has received much attention over the 80 or so years of aviation history, and that much has been accomplished to keep pace with increased sophistication of aviation operations and equipment.

It is apparent that exploration of the edges of the technical frontier demands creative ideas that can flourish only in a team environment with adequate funding and human resources. In the case of aviation, this means a constructive, competent and technically competitive partnership between government, manufacturing and airlines. Open communication is absolutely essential for progress.

Lastly, it appears that during the past 5-7 years, new forces have appeared that have interrupted the stability and continuity of research and development and forced the industry into economic problems that make the environment more hostile to continued safety improvement.

The most important factor is not the hostility threat itself; it is the early recognition of these new factors and a commitment by industry and government to compensate for their effects.

I hope that, as you continue this important workshop during the next two days, teamwork will be strengthened and that innovative new ideas will flow from the discussions that will yield practical and feasible methods for fuel containment and fire management.

Thank you for the opportunity to share these thoughts with you.

SESSION II: FUELS RESEARCH - GOVERNMENT

Chairperson: Dr. Homer Carhart

## Antimisting Fuel Breakup and Flammability\*

V. Sarohia, P. Parikh and G. Fabris  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

### SUMMARY

The breakup behavior and flammability of antimisting turbine fuels subjected to aerodynamic shear are investigated in this paper. Fuels tested were jet A containing 0.3 percent FM-9 polymer (developed by ICI Americas) at various levels of degradation ranging from virgin antimisting kerosene to neat jet A. The shearing air speeds employed ranged from 20 to 80 m/s (40 to 160 knots).

The misting behavior of the fuels was quantified by droplet size distribution measurements. A new technique based on high resolution laser photography and digital image processing of photographic records for rapid and automated determination of droplet size distribution was developed for this purpose. The flammability of flowing droplet-air mixtures was quantified by direct measurements of temperature rise in a flame established in the wake of a continuous ignition source. The temperature rise measurements were correlated with droplet size measurements. The mist flammability, defined in terms of a reduced

- 
- \* This work presents the results of one phase of research carried out at Jet Propulsion Laboratory, California Institute of Technology, Contract NAS7-918 Task Order RE152, Amendment 293, sponsored by DOT/FAA Technical Center, Atlantic City New Jersey Airport, NJ.
  - \* For further details refer to "Antimisting Fuel Breakup and Flammability" by P. Parikh, R. Fleeter, and V. Sarohia, DOT/FAA/CT-82/149, December 1983.

temperature, was found to be a function primarily of the mist SMD and was independent of the fuel dump rate.

The flame anchoring phenomenon associated with the breakup of a liquid fuel in the wake of a bluff body following ignition by a transient source was shown to be important in the context of a survivable crash scenario. A new pass/fail criterion for flammability testing of antimisting fuels, based on this flame-anchoring phenomenon, was proposed. Pass/fail boundary based on this criterion was found to be a strong function of both the airspeed and the degree of fuel degradation as measured by the filter ratio. Within the range of the fuel dump rates employed (10 to 40 gpm), it was not possible to have a self-supporting flame anchored in the wake of a bluff body (fail condition) for fuels having filter ratio larger than 8 and air speeds lower than 160 knots.

The role of various ignition sources and their intensity in ignition and post-ignition behavior of antimisting fuels was also investigated. It was found that the ignition source intensity plays a key role in determining whether or not ignition of a given droplet-air mixture will be achieved. The threshold ignition intensities to achieve ignition of various filter ratio fuels aerodynamically misted by a 100 knot wind were determined. Over a wide range of fuel dump rates and ignition source intensities in the present laboratory scale experiments, the proposed pass/fail criterion based on the flame anchoring phenomenon was

found to be independent of the fuel dump rate and the ignition source intensity.

The rate of flame spread on the surface of a pool of jet A and AMK fuels was investigated for various depths of fuel layer at ambient temperature condition. Within the uncertainty of the data, no significant difference between the flame spread rate over pools of Jet A and AMK fuels was observed. The flame spread rate generally increased from about 2 cm/sec to 3.5 cm/sec as the depth of the fuel layer was increased from 3 mm to 18 mm. The presence of a porous substrate (such as loosely packed soil) inhibits flame spread. Steady state flame spread over a fuel soaked bed of sand was 1/5 to 1/6 of the measured spread rate for a pure liquid layer.

Experiments were also performed to determine the flammability characteristics of jet A and AMK fuels under impact atomization scenario. Both jet A and AMK Fuel shielded from aerodynamic breakup was dropped onto ground fixed rough elements from different heights ranging from 6 to 30 ft. The impact (splash area) region also contained series of propane ignition sources. A pool of fuels (jet A or AMK) was also provided at the impact site. Preliminary data shows that fine mist generated by impact of a 5 gallon jet A test sample released from approximately 7 to 8 feet was enough to trigger a major ground pool fire. AMK dropped under identical test condition from even a height of 30 ft., provided ample suppression of ignition of splashed fuel and

any subsequent pool fires. This data may be important for crash scenarios where no aerodynamic misting occurs other than impact fuel release around a pool of fuel. It is inferred that under identical ignition, impact, and other crash conditions, elimination or significant delay of pool fires with AMK will result as compared to jet A.

## UK WORK ON SAFETY FUELS

S P Wilford

Materials and Structures Department  
Royal Aircraft Establishment

The UK programme on safety fuels has, from its inception, been a collaborative effort between the Royal Aircraft Establishment (RAE) and the Paints Division of ICI. Also, since 1978, there has been a Memorandum of Understanding between the UK and US covering work on this topic.

The main aim here has been to try and develop aircraft fuels which will be much less likely to ignite during a potentially survivable crash: an effective way of reducing the fire hazard in such circumstances is to lower the fuel's tendency to form flammable mists.

Over a period of some years ICI developed a number of anti-misting fuels, all of which were aviation kerosine modified by the addition of high molecular weight polymeric additives, the most promising candidate to date being FM9 anti-misting kerosine. A wide range of laboratory and larger-scale tests, both UK and US, indicated that this fuel had good fire suppressing properties in conditions relating to survivable crashes. Nevertheless, as everyone is now aware, if the ignition source is large enough and the aerodynamic conditions right, FM9 fuel will burn as shown in the CID last December, albeit with a reduced intensity compared to the base fuel.

Turning to matters other than fire resistance a safety fuel is useless unless it can be pumped into the aircraft fuel tanks, transferred from these to the engine and ultimately burned in a combustion chamber. Over several years much of the UK programme concentrated on the potential problems posed to aircraft and engine fuel systems by

FM9 fuel, which is a non-Newtonian fluid with some peculiar handling characteristics.

Starting with incorporation of the additive into fuel, consideration of this area indicated that the optimum method of introduction was by blending at the aircraft fuelling point. Further, practical considerations dictated that it should be added as a high-solids content slurry of the additive in a carrier fluid. Much effort by ICI and Shell Research went into defining the optimum composition for the carrier fluid and RAE work showed the importance of having a small proportion of water in the slurry in order to get acceptable dissolution. With regard to blending slurry into kerosine, RAE built two blenders, the second one being capable of preparing FM9 fuel at 50 gallons/minute. This work, coupled with later US work, indicates that there are no serious problems in preparing FM9 fuel from the slurry and kerosine.

Turning to airframe fuel systems aspects, early anti-misting fuels posed severe problems for tank boost pumps, particularly at low temperatures. However, FM9 fuel was shown to have pumping efficiencies not more than 25 - 30 per cent lower than those for kerosine over the temperature range ambient down to  $-35^{\circ}\text{C}$ , and some pumps had efficiencies that were only marginally different to kerosine over the same range. Another matter relevant to the airframe fuel system is that of water compatibility. Simple laboratory tests, where FM9 fuel is mixed with water giving copious gel, suggest horrendous compatibility problems, but despite this simulated flight studies by Shell Research and flight trials at RAE found no serious problems. Much more rigorous simulator tests by Boeing and the FAA's Convar 880 flight tests have confirmed this view.

Moving on to the engine and its associated hardware such as heat exchangers, fuel controllers and atomisers, early work showed that these

components would function correctly provided that FM9 fuel was degraded prior to reaching them (the term degraded refers here to breaking down the high molecular weight polymer into lower molecular weight fragments). The need then was to find the level of degradation required and how to achieve this efficiently.

Work by RAE and a number of UK companies (Lucas Aerospace, IMI Marston, Plessey Aerospace and Serck) showed, firstly, that FM9 fuel would have to be degraded to a filter ratio\* of 1.5 or less to be compatible with all components and, secondly, it could be degraded by a combination of high shear and extensional flow. Degraders were developed which would degrade fuel to the requisite level in one pass but they used significant amounts of energy to do this - about  $70 \text{ kWs l}^{-1}$ . Whilst seeking ways of reducing this RAE<sup>1</sup> carried out an analysis of degrader results which led to an empirical relationship between the inlet and outlet filter ratios of fuel going through a mechanical device and the specific power input at that point.

$$FR_O = 1 + \frac{(FR_I - 1)}{(1 + KP)}$$

$FR_O$  = outlet filter ratio

$FR_I$  = inlet filter ratio

P = specific power input  $\text{kWs l}^{-1}$

K = approximately 1.7 for many mechanical devices

This is an approximate relationship, with considerable limitations, but it did indicate that the energy required to degrade to a particular

---

\* Filter Ratio (FR) =  $\frac{\text{Filtration time for sample}}{\text{Filtration time for Jet A fuel}}$

using the RAE filter test apparatus.

filter ratio was markedly influenced by the inlet filter ratio to the device concerned. This led to considering the whole aircraft fuel system as the degrader: here, degradation is considered as a sequential process starting at the fuel tank and continuing in steps to the engine (Figure 1). This approach offered significant reductions in degradation energy requirements.

With respect to engine combustion, tests on an RB211 combustor can showed that, with FM9 fuel degraded to a filter ratio of 1.2, results under cruise and climb conditions were identical to those for kerosine but at the idle condition combustion efficiency was reduced slightly, resulting in increased gaseous emission.

Thus in mid-1982 a point was reached where it was considered that many of the problems in areas such as blending, degradation, engine combustion etc, had solutions, at least in principle. Since then, due to a number of constraints, the UK programme has concentrated on those areas where it was felt that there could be unresolved or long-term problems. Two principal areas have been covered here - cavitation studies and quality control.

Taking the cavitation studies first, one component test result had suggested that the use of FM9 fuel might lead to increased cavitation damage. This has been investigated in greater depth by the University College of Wales, Aberystwyth, though facilities at RAE were used for some experiments.

One part of this work<sup>2</sup> measured the cavitation threshold of a number of liquids including kerosine and FM9 fuel: the apparatus used is shown in Figure 2. The liquid under test is held in a vertical tube (1 metre long, 25 mm diameter) and during an experiment the tube is pulled downwards against the springs and then released. When it reaches the stop its motion is arrested and tension pulse is generated in the liquid column: the accompanying cavitation could be observed

visually and pressure changes were monitored by the transducer. The main point to emerge from this work is that kerosine has a higher cavitation threshold than FM9 fuel (Figure 3).

Another part of this work<sup>3</sup> used a perspex-bodied pump for flow visualisation (provided by Plessey Aerospace), a schematic diagram of which is shown in Figure 4. The pump was run at a number of preselected speeds and pressure pulses associated with cavitation were monitored by pressure transducers: high speed photography was used to determine the locus of cavitation. In the absence of cavitation the transducer response for both kerosine and FM9 fuel was of the type shown in Figure 5: analysis showed that the transducer was recording the working pump pressure. Under cavitating conditions the transducer response was typically of the form shown in Figure 6: this is a composite of the regular pump pressure response upon which are superimposed large, transient pressure peaks due to cavitation. High speed photography showed that cavitation originated from the trailing edges of gear teeth. One important finding was that there were approximately twice as many transients per unit time with FM9 fuel as with kerosine and damage to the perspex inserts in the pump was greater with FM9 fuel. Another result was that entrained gas suppressed the high pressure transients almost completely.

These results suggest that, for some components, the working life with FM9 fuel may be reduced as compared to kerosine.

Moving on to quality control, the two main methods used to assess the quality of FM9 fuel have been the orifice flow test and the RAE filter ratio test: both have at times given problems with poor repeatability and operator dependency, and on occasion these tests have missed changes in fuel quality that have only been detected at a later stage.

Jet thrust studies<sup>4</sup> had shown that FM9 fuel has viscoelastic properties and the normal stresses which are responsible for jet thrust differences also cause the trajectory of a jet to be modified. It was considered that a capillary trajectory method might offer a robust yet sensitive means of assessing the quality of FM9 fuel<sup>5</sup>.

The apparatus (Capillary Trajectory Rig - CTR) used is illustrated schematically in Figure 7. Studies here included the effect of deliberately varying FM9 fuel quality, change of concentration of additive, degree of degradation of fuel and alteration of the  $\frac{1}{d}$  of the capillary. The results with FM9 fuel of deliberately varied quality are shown in Figure 8 as a plot of impact distance against applied pressure. In the main the results agreed with orifice flow data, sample 16 (orifice flow value 2.4) giving the shortest trajectory and sample 18 (orifice flow value 4.2) the longest. However, samples 20 and 21 had the same orifice flow value but gave significantly different trajectories: other data suggested that there could be differences between these samples.

The effect of degradation is illustrated in Figure 9: fuel for this test was degraded by up to 4 passes through a laboratory blender. The results show good discrimination between samples but also indicate that the test is of little value at filter ratios less than 10 with the particular capillary used.

From the above and other tests it was felt that, following further correlations between the CTR and fire tests, a pass/fail line could be placed on Impact distance/Applied pressure graph. Overall it was concluded that the CTR offered:

- a. a more sensitive means of quality control than those used to date,
- b. it could, with further work, be calibrated to give the margin of fire safety,

c. provide useful rheological information.

Returning now to the CID test, some very recent work at Portsmouth Polytechnic<sup>6</sup> may help to explain the unexpected amount of fire which occurred. These studies, using a mist measuring device, indicate that at airflows of about 150 knots a small proportion of very fine fuel mist occurs with undegraded FM9 fuel. Although the proportion is low, a few per cent or less, in the case of a very large fuel release such as in the CID (2500 - 3000 gallons) this could lead to significant amounts of fine fuel mist. Given the presence of a bluff body, its accompanying recirculation zone could act as a concentrator of the fine fuel mist as this will readily be swept into that zone: the mist concentration may then exceed the lower ignition limit and lead to a sustained fire. It should be stressed that the initial cause of the fire, the 'opened-up' engine, is not in doubt but the effect outlined here could have helped to make matters worse. Work is continuing in this area to try and quantify the amount of fine mist as a function of airflow velocity.

Overall the UK has pursued its research to determine whether the handling and systems aspects of AMK could be resolved satisfactorily: the answer on both counts appears to be yes. However, the CID has shown that in some crash scenarios AMK can be disappointing with a consequent reduction on the "benefits" side of the equation.

© Controller, Her Majesty's Stationery Office, London, 1985

# REFERENCES

- | No | Author(s)                                    | Title, etc  |
|----|--|---|
| 1  | E A Timby                                    | Some notes on the degradation of anti-misting kerosine.<br>RAE Technical Memorandum EP654 (1981).                                     |
| 2  | G D N Overton<br>P R Williams<br>D H Trevena | The influence of cavitation history and entrained gas on liquid tensile strength.<br>J Phys D: Appl Phys, <u>17</u> , 979-987 (1984). |
| 3  | P R Williams                                 | Cavitation properties of liquids with special reference to aviation safety fuels.<br>PhD Thesis, University of Wales (1984).          |
| 4  | I Faul                                       | Shear and extensional flow characteristics of FM9 safety fuel.<br>RAE Technical Report 83059 (1983).                                  |
| 5  | E A Timby<br>K R Hillier<br>S P Wilford      | RAE Technical Report, to be published.  |
| 6  | A Khalil                                     | Private communication.  |

FIG 1

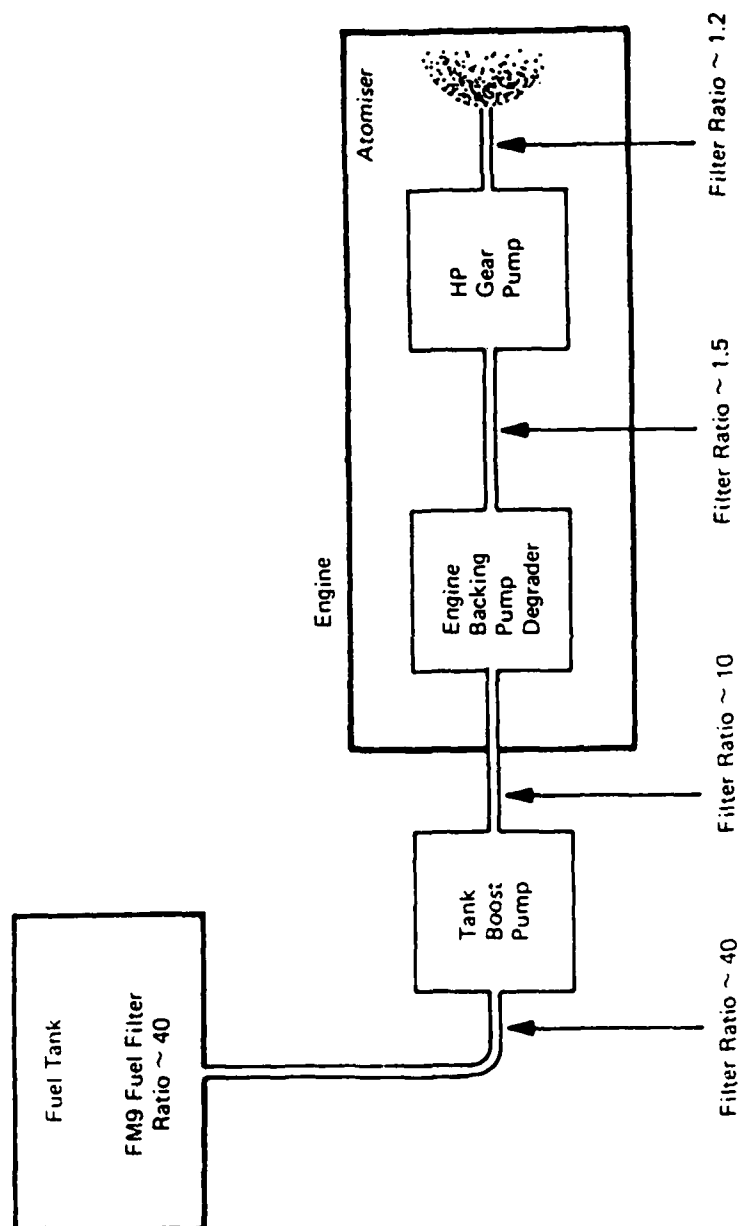


FIG 1 SEQUENTIAL DEGRADING

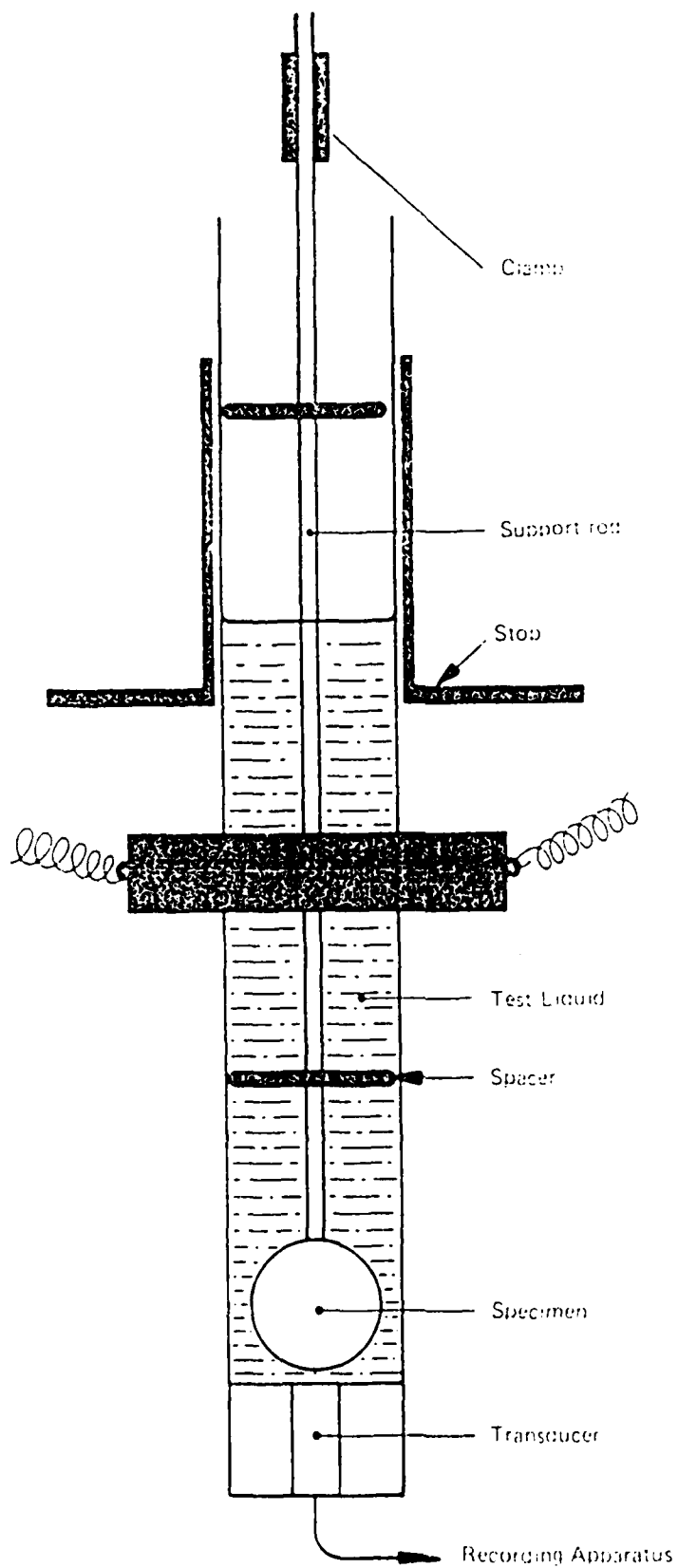


FIG 2 SCHEMATIC DIAGRAM OF APPARATUS FOR STUDYING CAVITATION DAMAGE AND BUBBLE DYNAMICS

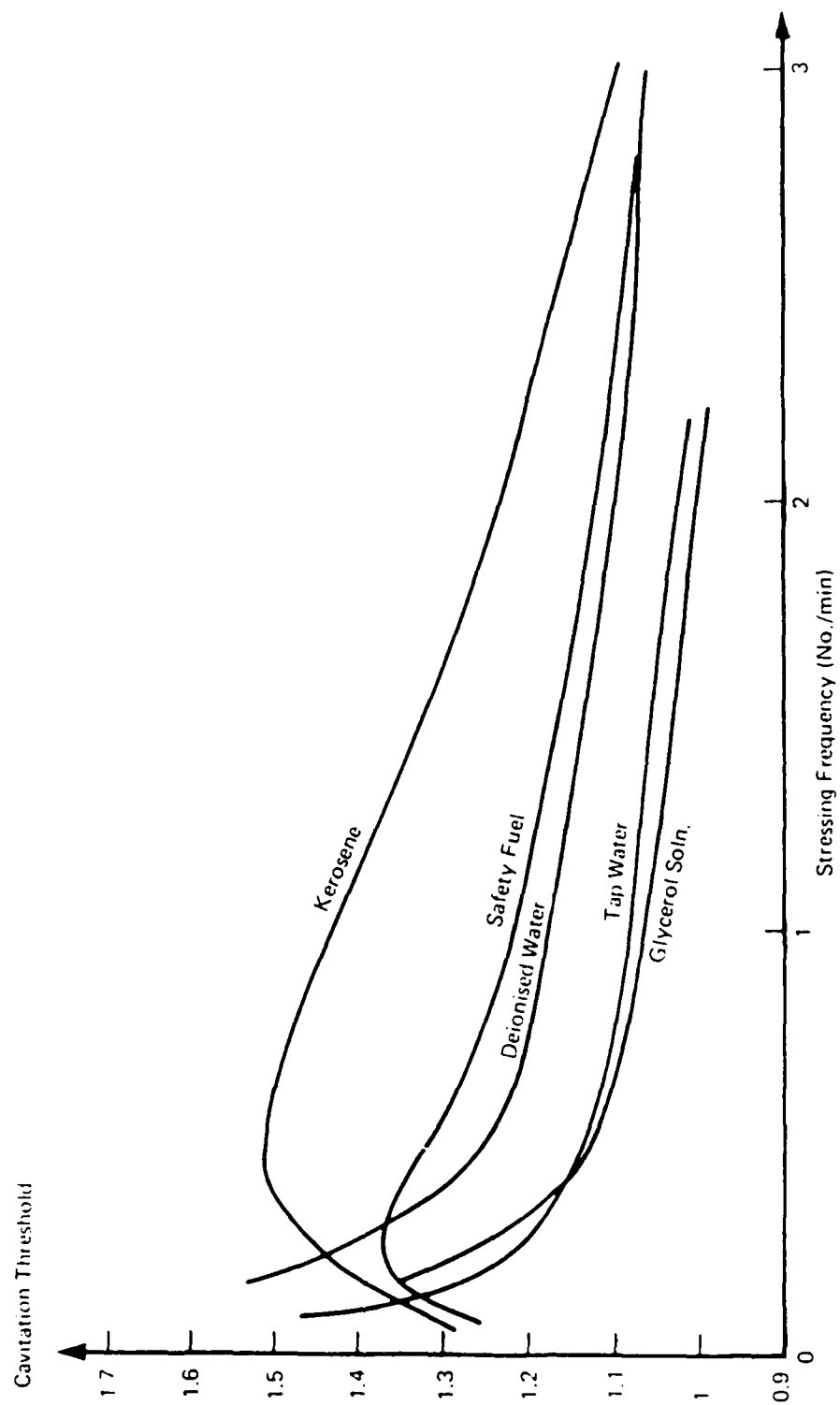


FIG 3 PLOT OF CAVITATION THRESHOLD AGAINST STRESSING  
FREQUENCY FOR 5 LIQUIDS

FIG 4

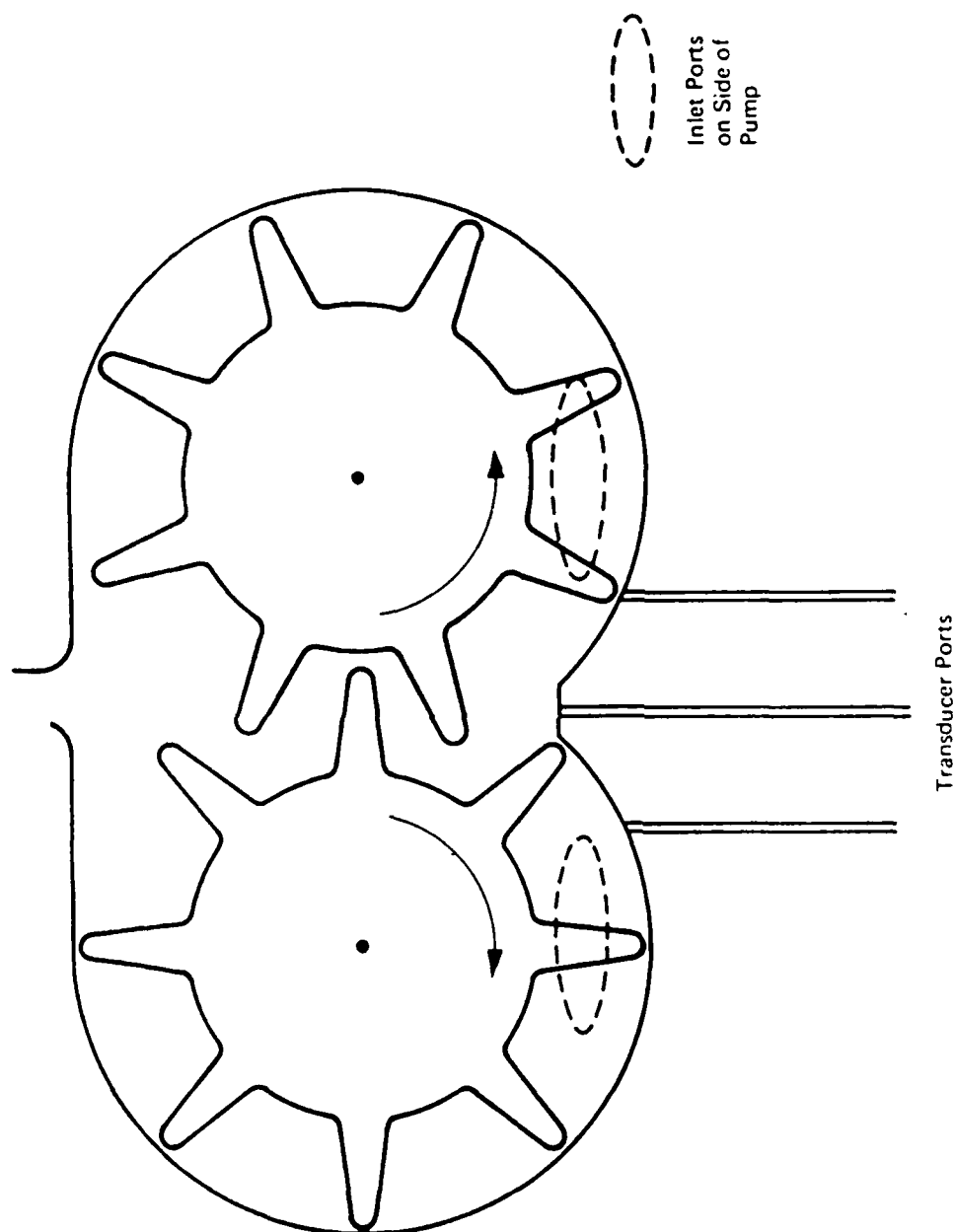
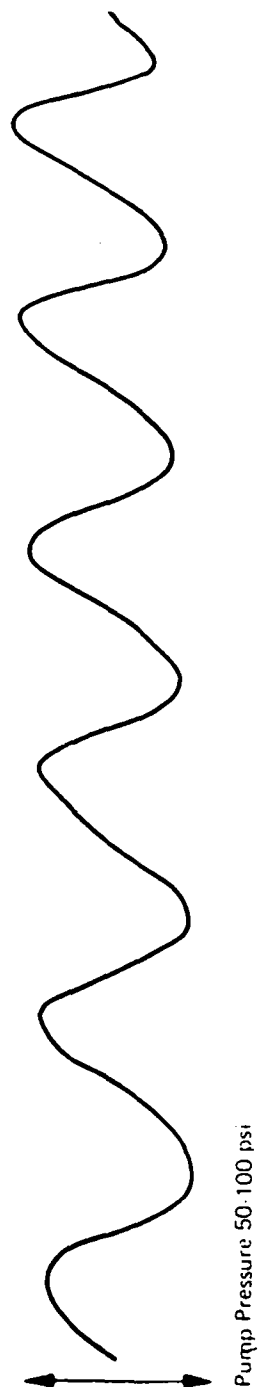


FIG 4 SCHEMATIC OF PUMP, GEAR TEETH AND POSITION  
OF TRANSDUCER PORTS

TRANSDUCER TRACE - LOW PUMP SPEED, NO CAVITATION, NO ENTRAINED AIR



Amplitude Corresponds to Pump Pressure as Measured by Gauges on Both Inlet and Outlet

FIG 5

FIG 5

TRANSDUCER TRACE ... HIGH PUMP SPEED, CAVITATION, NO ENTRAINED AIR

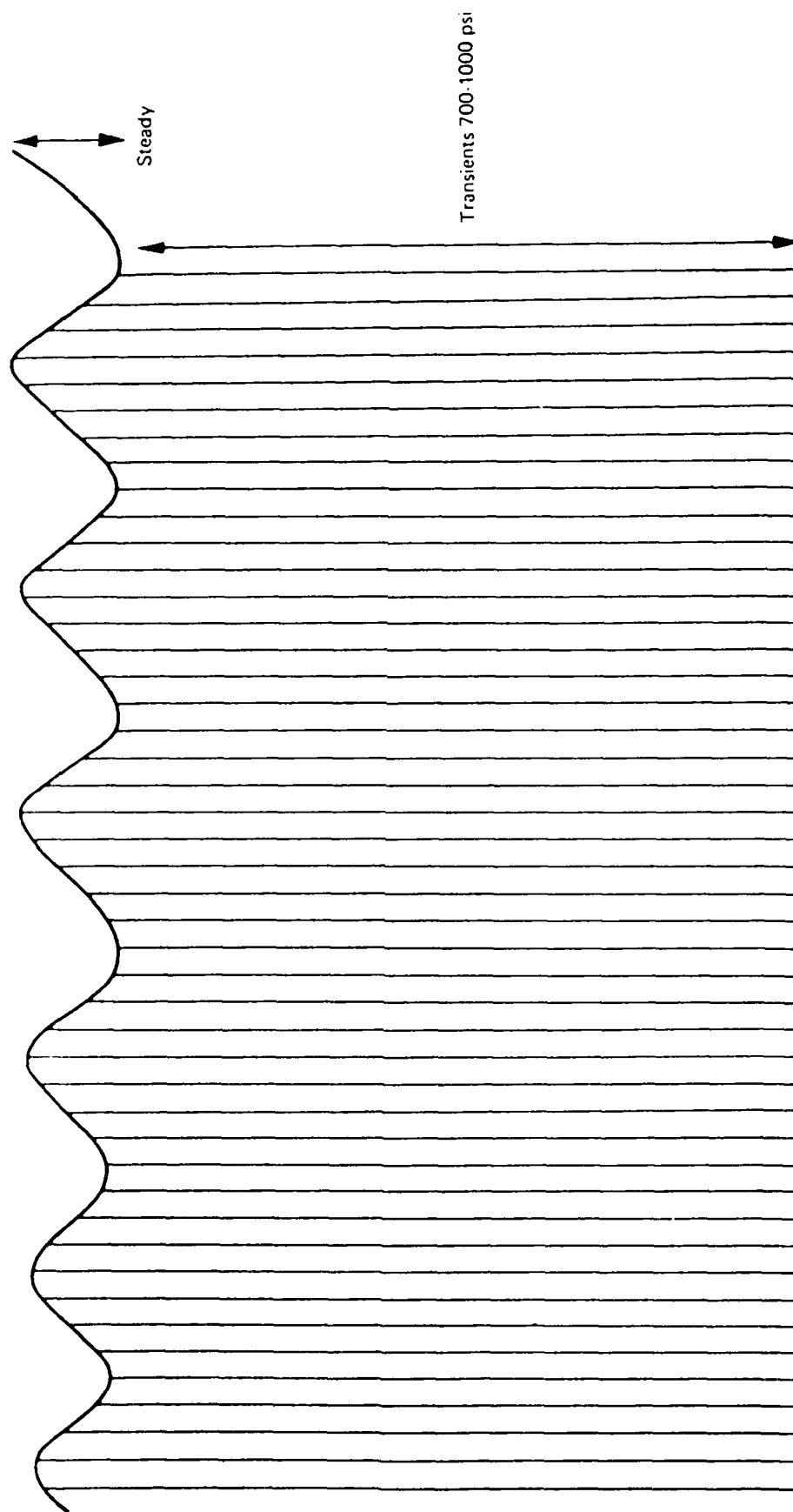


FIG 6

FIG 6

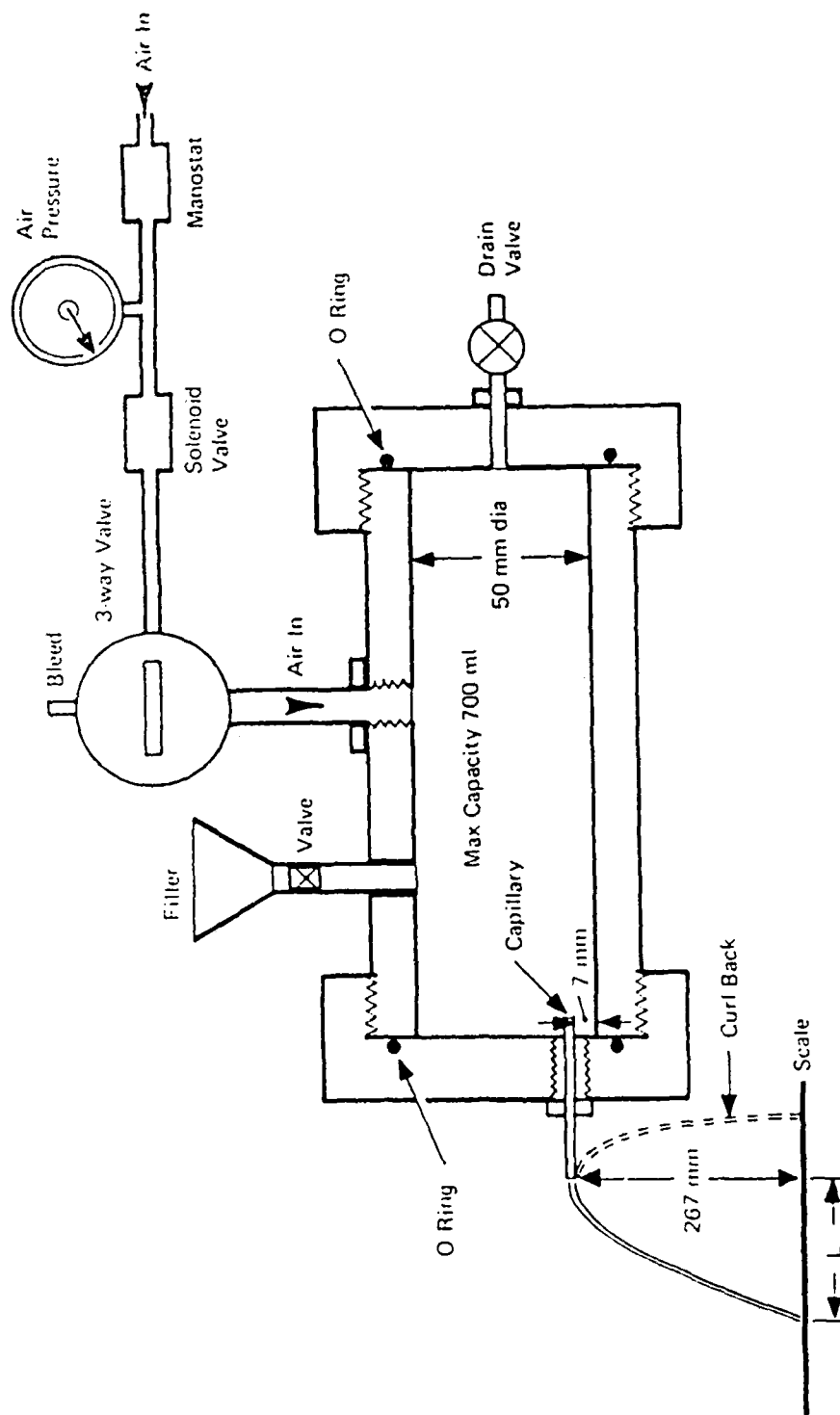


FIG 7 DIAGRAMMATIC SKETCH OF TEST RIG

FIG 8

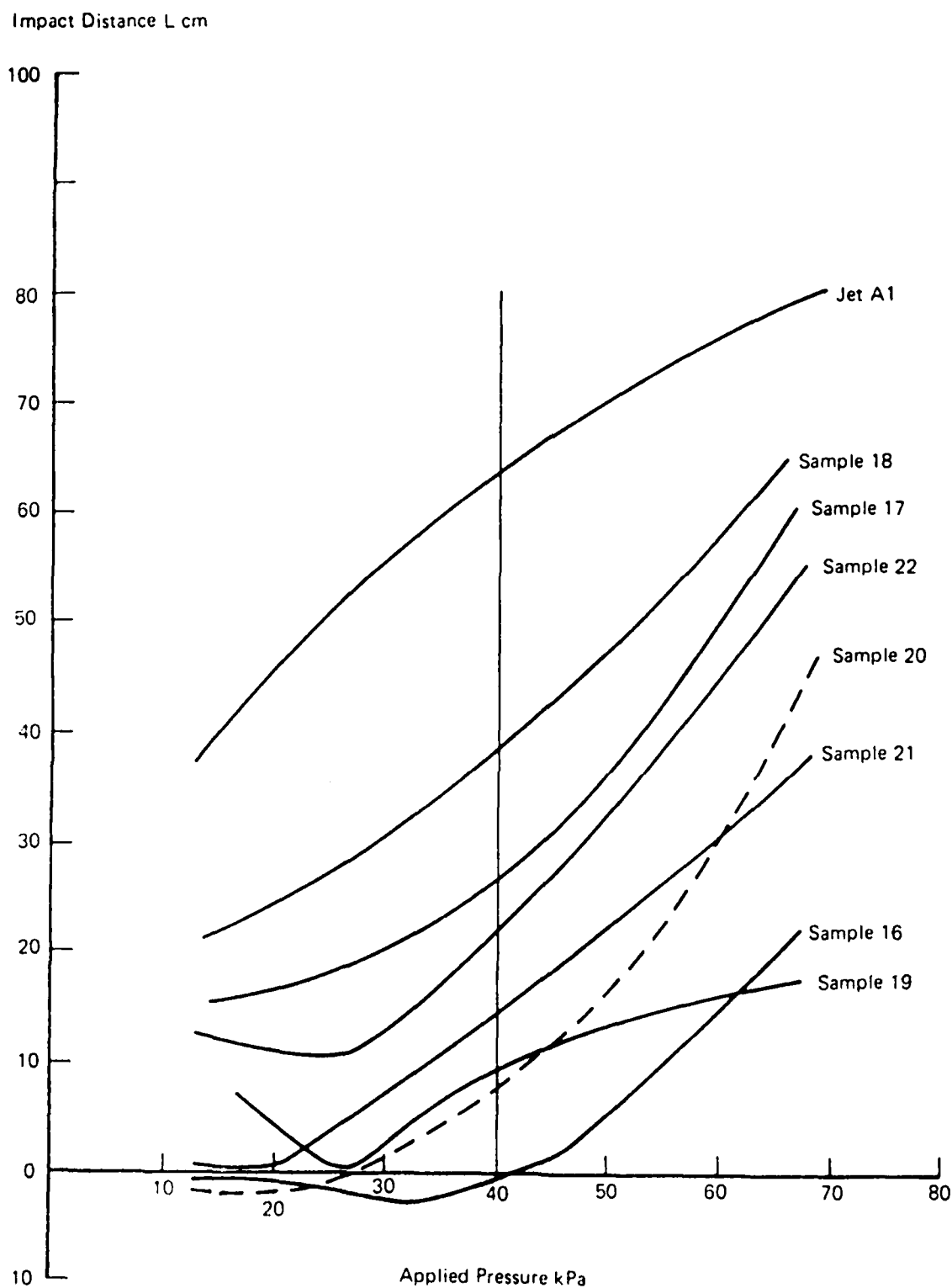


FIG 8 IMPACT DISTANCE vs APPLIED PRESSURE. FM9 SAMPLES

FIG 9

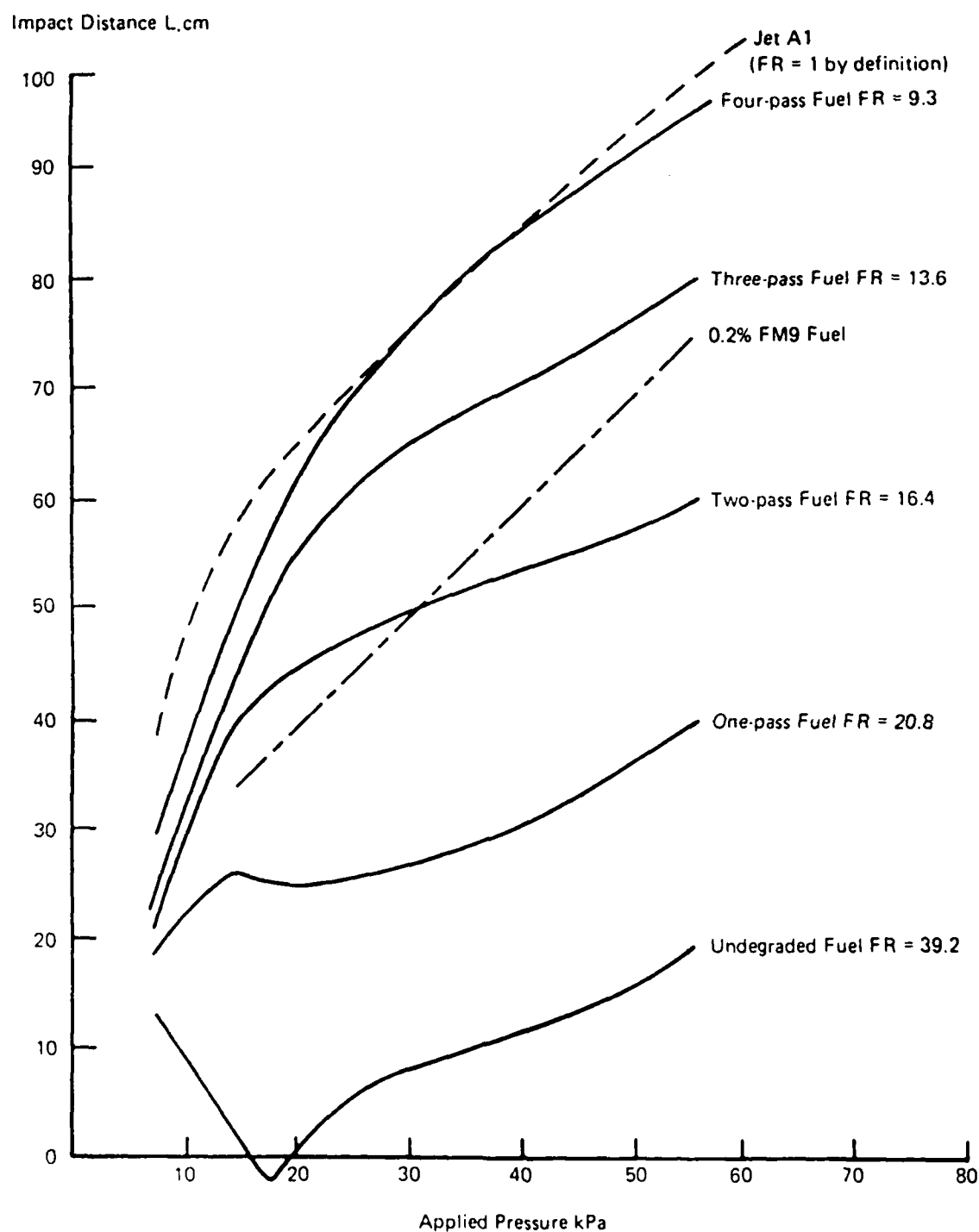


FIG 9 IMPACT DISTANCE vs APPLIED PRESSURE. EFFECT OF DEGRADATION

HEAT TRANSFER, FRICTION, AND RHEOLOGICAL CHARACTERISTICS  
OF ANTIMISTING KEROSENE\*

E. Matthys and V. Sarohia  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

SUMMARY

Experiments have been performed to determine the skin friction and heat transfer behavior of antimisting kerosene in pipe flows. The additive used in the AMK was FM-9 developed by Imperial Chemical Industries. AMK has been developed as an aviation safety fuel to reduce post-crash fires. The principal aim of the resent investigation was to determine the modifidication in flow and heat transfer behavior caused by the presence of the anti-misting polymer additive in jet fuel.

---

\* This work presents the results of one phase of research carried out at Jet Propulsion Laboratory, California Institute of Technology, Contract NAS7-918 Task Order RE152, Amendment 293, sponsored by Department of Transportation/Federal Aviation Administration Technical Center, Atlantic City Airport, NJ, under Agreement No. DTFA03-8000215.

For further details refer to:

- (1) "Frictional Characteristics and Heat Transfer of Antimisting Fuel in Tubes," by J. Watt and V. Sarohia DOT/FAA/CT-82/20, August 1982.
- (2) "An Experimental Study of Convective Heat Transfer, Friction and Rheology for Non-Newtonian Fluids: Polymer Solutions Suspension of Fibers, and Suspension of Particulates," Ph.D Thesis, Division of Engineering and Applied Sciences, California Institute of Tehcnology, June, 1985.
- (3) "Heat Transfer, Friction and Rheological Characteristics of Antimisting Kerosene," to be published as a FAA report.

The test tube is made of extruded seamless stainless steel of approximately 8mm inner diameter and about 5 meters long. Reynolds number between  $5 \times 10^3$  to  $10^5$  based on jet A viscosity were investigated. Tube Reynolds numbers in aircraft fuel systems can be as high as  $10^4$  to  $10^5$  under cruise and takeoff conditions. The heat transfer in the present experiment was obtained by electrically heating the wall, which produced an approximately constant heat flux. Pressure and temperature differentials at various locations along the tube were measured to determine the fuel skin friction and heat transfer characteristics. Complex viscous behavior of AMK were also studied within capillary tubes to explain the unusual friction and heat transfer results.

The present study indicates that the AMK skin friction versus Reynolds number, or Nusselt number versus Reynolds number behavior, can be divided into three regions: (1) Newtonian laminar region, (2) shear-thickening transition region, and (3) drag-reducing turbulent region. At low flow rates, AMK has Newtonian behavior, i.e., constant viscosity. At a certain critical wall shear rate which depends on the fuel temperature and additive concentration, shear thickening occurs and causes a large increase in skin friction and heat transfer rates. For some fluids such as 0.1 percent FM-9 AMK and partially degraded AMK the second region is not observed. In the third region, the skin friction and heat transfer rates drop rapidly and fall below the predicted Newtonian flow skin friction and heat transfer value; e.g. for 0.3 percent FM-9 AMK at a temperature of  $20^\circ\text{C}$ ,

these values coincide with Newtonian values at solvent Reynolds number,  $Re_s$ , equal to  $2.2 \times 10^4$  and  $10^4$ . Beyond these points, there is a reduction in skin friction and heat transfer rates.

Because of the high viscosity and viscoelasticity of the AMK, before injecting into the engine combustion chamber, AMK should be degraded. Skin friction and heat transfer measurements showed similar behavior as jet A when equilibrated AMK was degraded by passing through a needle valve (pressure drop 4000 psi).

In summation, however, it should be added that within the present experimental limits, there is some interesting flow behavior in the shear-induced transition region. From a design point of view partially degraded FM-9 AMK (as will be seen by engine fuel system) does not drastically modify the frictional and heat transfer characteristics of the fuel. Moreover, highly degraded equilibrated AMK showed essentially identical skin friction and heat transfer behavior as jet A.

US ARMY FIRE RESISTANT FUEL (FRF) PROGRAM  
PRESENTATION TO FAA AVIATION FUEL SAFETY MEETING

by Dr. Forrest W. Schaeckel

ABSTRACT

The U. S. Army has a requirement for a diesel fuel that will perform satisfactorily in diesel powered combat equipment but would self-extinguish in case of ignition by ballistic penetration on other unwanted ignition source. Six generations for fire-resistant fuel have been investigated by the Army, the latest approach involves the inclusion of surfactant-stabilized emulsified water in diesel fuel. Flammability evaluations demonstrated that such aqueous microemulsions yielded diminished mist flammability while either eliminating pool burning or providing rapid self-extinguishment of pool fires, even at fuel temperatures more than the 10°C above the base fuel flash point. The FRF has excellent pool-fire resistance; however, logistical constraints and low-temperature instability of the microemulsion type FRF preclude Army-wide adoption of this fuel. Current effort is to resolve technical issues related to fielding the fuel. A Short-Term Advisory Services team recommended alternative approaches. Their recommendation led to ballistic tests with cooled fuel and antimisting agents. A movie was shown of selected ballistic tests using 90 mm snaped charges against armored personnel carrier fuel tanks.

## U.S. Army Fire-Resistant Fuel (FRF) Program

### VU1. U.S. ARMY FIRE-RESISTANT FUEL (FRF) PROGRAM

The U.S Army has a special requirement for a diesel fuel that will perform satisfactorily in diesel-powered combat vehicles, but will self-extinguish in case of ignition by ballistic penetration or other unwanted ignition sources. An R&D program has been ongoing for several years with the initial effort directed to reducing fires in helicopter crashes; especially in other-wise survivable crashes. The thrust of the Fire-Resistant Program changed as a result of the Israeli conflict where combat tank fires were reported as the major cause of equipment loss and personnel deaths. During this same time frame improved safety features aboard helicopters practically eliminated fatalities in "survivable" helicopter crashes. A crash was judged "survivable" or "non-survivable" based on the extent of structural damage.

### VU2. TECHNICAL APPROACH FOR FRF FORMULATION

The reduction of personnel losses and vehicle damage can be obtained through fuel modification by (1) Control of pool burning, (2) Reduction of fuel misting and by having reduced fuel flammability, and (3) Augment existing on board suppression systems.

### VU3. PREVIOUS FRF RDTE

Six generations of fire-resistant diesel fuel have been investigated by the Army and these are shown here. There are essentially three different approaches; (1) incorporating fire-extinguishing agents (Halons) into the fuel, (2) using antimisting agents or (3) adding water in the form of an emulsion. Although the microemulsion with antimisting provided the most protection, the difficulty of blending large quantities of such fuels under field conditions shifted the program emphasis to microemulsion without antimisting agents. The last approach on the chart was entering advanced development when logistical constraints and low temperature performance problems stopped program development for almost two years.

### VU4. TECHNICAL CHARACTERISTICS OF PROPOSED FRF

This viewgraph compares the translucent microemulsion on the left and the macroemulsion in the center with neat diesel fuel.

### VU5. FRF PHYSICAL AND CHEMICAL PROPERTIES

The microemulsion FRF results in changes in fuel properties as shown on this chart. Although the pour point is not changed, the microemulsion becomes milky upon cooling so that the cloud-point test is meaningless and even though the pour point is not changed; low temperature filterability through suction type filters is not possible. The addition of water increases the density and viscosity and reduces the heat of combustion and the cetane number of the base fuel.

#### VU6. M 113 FRF TEST

This viewgraph compares the results of neat and FRF when impacted by a 3.2 inch precision shaped charges. The fuel is heated to 77°C to simulate a worst case of diesel fuel heating caused by fuel recirculation in a diesel engine. Diesel fuel is used to cool fuel injectors in diesel engines.\_

#### VU7. ACCOMPLISHMENTS

The U.S. Army FRF Program has produced these results; HOWEVER.

#### VU8. SWA (Southwest Asia) DEPLOYMENT (Worst Case)

Logistical problems were identified by the Army supply activities with the potential use of FRF. This viewgraph shows the needs of a Heavy Corps in combat. The new supply items - emulsifier pre-mix and water present logistical problems which cannot be handled with current personnel and fuel handling equipment.

#### VU9. RESOLUTION OF TECHNICAL ISSUES

The Under Secretary of the Army has expressed interest in the Army using FRF. His interest has revived the R&D effort on FRR. This list of technical issues represents the goals of the current effort. The results of this effort will be used to quantify the benefits and penalties of using FRF and will provide data for the development of deployment plans achievable with the FRF microemulsion.

#### VU10. VISCOSITY OF ANTIMISTING POLYMER SOLUTIONS IN THE TEST BASE FUEL

A search for additional approaches to fire reduction was conducted and a Short-Term Advisory Service team assembled by the Army Research Office suggested fuel cooling and antimisting agents as potential approaches. Ballistic impact data (shaped-charge) were not available on such fuels there a series of tests was conducted by the TERA group of New Mexico Institute of Mining and Technology. Some of the properties of the fuels used for these tests are shown on this viewgraph. Notice the flash point of the base fuel (142°F) and the increase in viscosity caused by antimisting agents especially at low temperature.

VU11-16 Show the test set up for the ballistic tests at TERA. These viewgraphs will be followed by a motion picture film of some selected tests.

VU17. CONCLUSIONS OF APC BALLASTICS TESTS WITH 90mm HEAT ROUNDS

The energy of the 90mm shaped-charge overwhelms any protection against fire resulting from fuel cooling. It was also concluded that the addition of a high concentration 0.35% antimisting additive does not reduce fire susceptibility if the fuel temperature is near flash point. There is potential for reducing fires with combinations of fuel cooling and high concentration of antimisting agents; however, logistic and performance problems (high viscosity at low temperature) may make such approaches impractical for Army-wide use. Future Army effort--follow on to current effort--will depend on the resolution of the technical issues related to fuel mixing and handling and performance in Army combat equipment.

NARRATION OF 16mm FILMCLIP:  
BALLISTIC TESTS AT SOCORRO NM

The film clip contains edited footage of four ballistic tests using a 90 mm shaped charge (HEAT Warhead) against cooled diesel fuel and fuel containing either 0.2% or 0.35% AM-1 antimisting agent. A test with only water in the fuel tank shows the fire related only to the warhead. Each test has footage of two outside overall views (24 FPS and 4000 FPS) of the Armored Personnel Carriers and one inside view (1000 FPS) of the personnel compartment. The tests shown are listed below:

<u>Fuel</u>	<u>Fuel Temperature (°F)</u>
1. Neat Diesel Fuel (DF-2)	38
2. DF-2 + 0.2 wt% AM-1	60
3. DF-2 + 0.35 wt% AM-1	60
4. DF-2 + .35 wt% AM-1	125
5. Water	46

The flash point of the base fuel was 142°F and 50 gallons of fuel in a 60 gallon tank was the target. The shaped charge first penetrated 1.5 in of aluminum armor. The results of the test are as follows:

1. Neat Diesel Fuel (DF-2) 38°F

The shaped charge perforated the aluminum armor and both sides of the fuel cell. The end of the fuel cell opened along the weld, and all the fuel drained onto the floor. An intense pool fire resulted, but there was no ground fire. After several minutes of intense burning, the fire was suffocated by closing the rear door. Fuel tank pressure peaked at 61 psi (42kPa), and the high temperature in the personnel compartment was 1576°F (858°C).

2. DF-2 + 0.2 wt% AM-1 (60°F)

The shaped charge perforated the aluminum armor and both sides of the fuel cell. The end welds of the fuel cell split, and all fuel was emptied. An intense fire developed that was extinguished by closing the rear door. The fire suffocated in about 1 minute. Tank pressure peaked at 215.3 psi (1.49 MPa), and the high temperature in the personnel compartment was 1439°F (782°C).

3. DF-2 + 0.35 wt% AM-1 (60°F)

The shaped charge perforated the aluminum armor and both sides of the fuel cell. The fuel cell end welds were split, and all fuel was expelled. No pool fire was produced, and only a momentary increase in temperature was recorded. The peak fuel cell pressure was 124 psi (855 kPa), and the high temperature in the personnel compartment was 84°F (29°C).

4. DF-2 + 0.35 wt% AM-1 (125°F)

The shaped charge perforated the aluminum armor and both sides of the fuel cell. One end of the fuel cell was blown off. Fuel was expelled through the open end and circled the APC in large flowing sheets, igniting as it circled into the heat round fireball. A momentary bright flash occurred which quickly subsided, leaving small fires around the interior perimeter of the PAC. These later grew into a large intense fire. No pressure gauge was used, but the high temperature in the personnel compartment was 2000°F (1093°C).

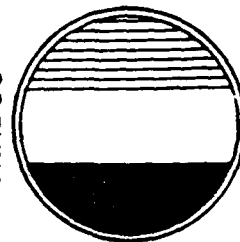
5. Water (46°F)

The shaped charge perforated the aluminum armor and both sides of the fuel cell. The high temperature in the personnel compartment was 61°F (16°C), and the peak fuel cell pressure was 121 psi (834 kPa). The peak personnel compartment pressure was 9 psi (62 kPa).



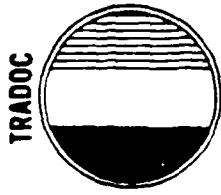
# U.S. ARMY FIRE RESISTANT FUEL (FRF) PROGRAM

TRADOC





# TECHNICAL APPROACH FOR FRF FORMULATION



- CONTROL OF POOL BURNING
- REDUCTION OF FUEL MISTING
- AUGMENTS EXISTING ON-BOARD  
SUPPRESSION SYSTEM

AO-A168 784

PROCEEDINGS OF FUEL SAFETY WORKSHOP HELD AT ALEXANDRIA  
VIRGINIA ON 29 OCT. (U) FEDERAL AVIATION ADMINISTRATION  
WASHINGTON DC PROGRAM ENGINEE.. 31 DEC 83

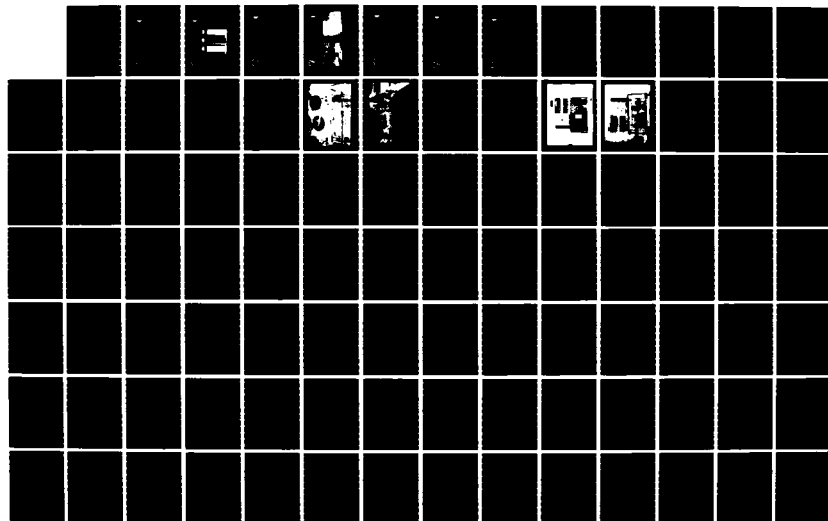
3/4

UNCLASSIFIED

DOT/FAR/PM-86/13

F/G 21/4

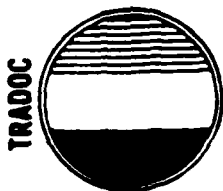
NL







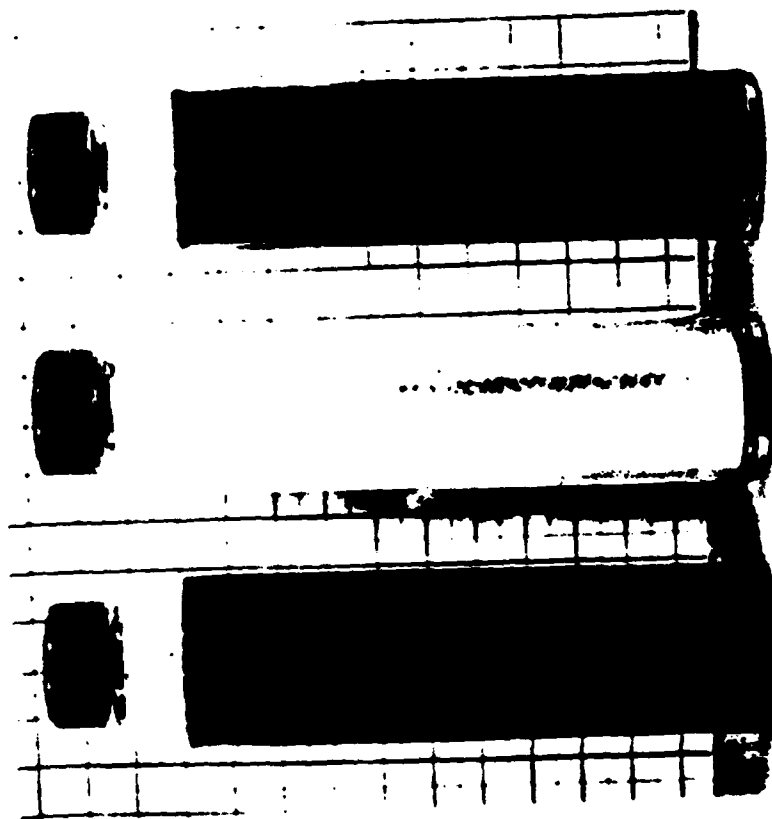
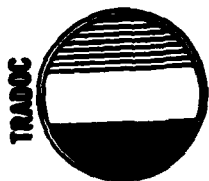
# PREVIOUS FRF RDTE



<u>PERIOD</u>	<u>TYPE</u>	<u>COMPOSITION</u>
1972-1976	HALOGENATED	DIESEL FUEL WITH 5% BROMO-CHLOROMETHANE
1974-1976	MACROEMULSION	DIESEL FUEL WITH 10% WATER AND 2% EMULSIFIER
1974-1977	ANTIMISTING	DIESEL FUEL WITH 0.5% ANTI-MISTING ADDITIVE
1976-1979	MICROEMULSION WITH ANTIMISTING	DIESEL FUEL WITH 5% WATER, 3% EMULSIFIER, AND 0.5% ANTI-MISTING ADDITIVE
1976-1981	MICROEMULSION	DIESEL FUEL WITH 10% WATER AND 6% EMULSIFIER
1981-1983	MICROEMULSION	DIESEL FUEL WITH 10% WATER AND 12% EMULSIFIER PREMIX



# TECHNICAL CHARACTERISTICS OF PROPOSED FRF



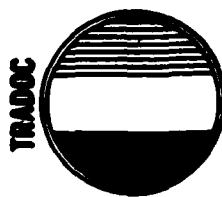
NEAT  
DIESEL  
FUEL  
(DF-2)

88% DF-2  
2% EMULSIFIER  
10% WATER

FRF  
78% DF-2  
12% PRE-MIX  
10% WATER



# FRF PHYSICAL AND CHEMICAL PROPERTIES



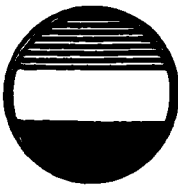
<u>PROPERTY</u>	<u>FRF*</u>	<u>DIESEL FUEL BEFORE CONVERSION</u>
DENSITY @ 15.6°C	0.887	0.853
POUR POINT, °C	-38	-36
VISCOSITY, cSt @ 40°C	3.9	2.6
HEAT OF COMBUSTION, MJ/kg	36.9x10 <sup>3</sup>	42.9x10 <sup>3</sup>
CETANE NO.	32	42

\* PRODUCTION OF A STABLE FUEL (I.E., 3 MONTHS OR MORE)  
REQUIRES WATER HARDNESS (I.E., TOTAL DISSOLVED SOLIDS)  
NOT TO EXCEED 500 PPM



## M 113 FRF TEST

TRACOC



**DRAINING OF NONIGNITED FUEL  
AFTER FRF TEST**



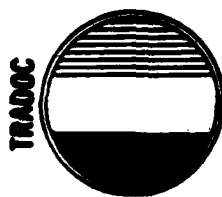
**FLAMING WITHIN AND BENEATH  
VEHICLE DURING NEAT FUEL TEST**



**DEMONSTRATION OF EFFECTIVENESS OF FIRE-RESISTANT  
DIESEL FUEL (FRF) AT 77°C IN M-113 ARMORED PERSONNEL  
CARRIER USING 3.2-INCH PRECISION SHAPED CHARGES  
(54°C BASE FUEL FLASH POINT)**



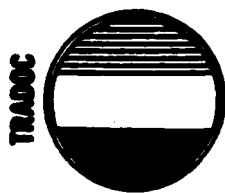
## ACCOMPLISHMENTS



- FRF FORMULATION IS COMPLETE
- BALLISTIC TESTS ARE PROMISING
- PRELIMINARY ENGINE TESTS ARE PROMISING
- PROTOTYPE MIXER IS DEVELOPED



# SWA DEPLOYMENT (WORST CASE)



## HEAVY CORPS — DIESEL FUEL CONSUMPTION DATA — SWA (IN GALLONS PER DAY)

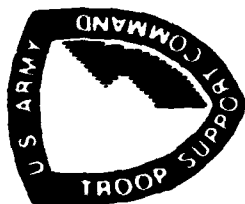
**TOTAL DIESEL FUEL REQUIREMENT**      **1,470,762**

**FRF ALL EQUIPMENT**

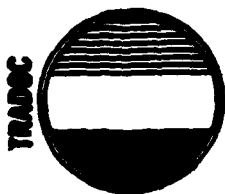
**DIESEL FUEL**      **78%**      **1,147,195**

**PRE MIX**      **12%**      **176,492**

**WATER**      **10%**      **147,075**



# RESOLUTION OF TECHNICAL ISSUES



- RESOLVE FUEL FILTER PLUGGING PROBLEM
- ASSESS IMPACT OF FRF TO ANCILLARY EQUIPMENT
- QUANTIFY VEHICLE POWER LOSS
- DEMONSTRATE FRF PRODUCTION AT LOW TEMPERATURES
- ASSESS TRANSPORTABILITY AND STORABILITY
- DEVELOP METHODS FOR OBTAINING SUFFICIENTLY PURE WATER
- ASSESS THE MILITARY VALUE OF FRF

## VISCOSITY OF ANTIMISTING POLYMER SOLUTIONS IN THE TEST BASE FUEL

AM-1 CONCENTRATION, WT%	VISCOSITY, cSt AT		
	0° C	40° C	100° C
0.0	3.3	1.55	—
0.20	24.3	8.8	4.0
0.35	35.1	15.2	6.8
0.55	99.7	37.9	22.1

## PROPERTIES OF DF-2 FUEL USED IN BALLISTICS TESTS

FLASH POINT, °F (°C)	142 (61)
CLOUD POINT, °F (°C)	—40 (—40)
FREEZE POINT, °F (°C)	—47 (—44)
VISCOSITY, 40° C, cSt	1.55
VISCOSITY, 0° C, cSt	3.3

## **CONCLUSIONS OF APC BALLISTICS TESTS WITH 90-mm HEAT ROUNDS**

---

- 1. COOLING OF NEAT DF-2 (100° F BELOW FLASH POINT) IN THE FUEL CELL DOES NOT REDUCE FIRE SUSCEPTIBILITY.**
- 2. EVEN A HIGH CONCENTRATION (0.35 WT%) OF ANTIMIST ADDITIVE (AM-1) DOES NOT REDUCE FIRE SUSCEPTIBILITY IF THE FUEL TEMPERATURE IS NEAR FLASH POINT.**
- 3. THE COMBINATION OF HIGH CONCENTRATION OF AM-1 AND FUEL COOLING REDUCES MIST FIREBALL. IT MAY PREVENT POTENTIAL POOL FIRES.**
- 4. RECOMMEND INVESTIGATIONS WITH COMBINATION OF AM-1 AND WATER IN THE DF-2.**

## CONTINUOUS INLINE BLENDING OF ANTIMISTING KEROSENE\*

P. Parikh, A. Yavrouian and V. Sarohia  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

### ABSTRACT

A continuous inline blender was developed at JPL to blend precisely metered quantities of ICI developed polymer slurries with a stream of Jet A fuel. The inline blender was used to produce 5 to 10 gallons per minute of freshly blended AMK. The proprietary ICI slurries made of FM-9 powder and other variants in glycol carrier fluid with powder loading in the range of 25 to 33 percent by weight were employed. Depending upon the polymer particle size and powder loading, the slurry consistency ranged from "free flowing" to a "paste" with viscosity in the range 5000 to 100,000 centipoise.

The key element in the inline blender was a static mixer placed immediately downstream of the slurry injection point. The static mixer achieved a rapid dispersion of the slurry in jet A stream, which resulted in a homogeneous suspension of polymer particles in jet A. The inline blender employed a positive displacement gear pump for jet A and a progressive cavity rotary

---

\* This work presents the results of one phase of research carried out at Jet Propulsion Laboratory, California Institute of Technology, Contract NAS7-917, Task Order RE 152, Amendment 293, sponsored by DOT/FAA Technical Center, Atlantic City Airport, N.J. under agreement No. DTFA03-80-A-00215.

\* For further details refer to "Antimisting Kerosene: Development of a Continuous 10GPM Inline Blender," by P. Parikh, A. Yavrouian, and V. Sarohia, DOT/FAA/CT-85/12, April 1985.

screw pump for slurry pumping. Turbine flow meters were employed for Jet A metering while the slurry flow rate was calibrated against the pressure drop in the injection tube. While using one of the FM-9 variant polymer slurries, a provision was made for a time delay between the addition of slurry and the addition of amine sequentially into the jet A stream.



CONTINUOUS INLINE BLENDING OF ANTIMISTING KEROSENE

P. PARIKH  
A. YAVROUIAN  
V. SARUHIA

JET PROPULSION LABORATORY  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA 91109



#### FUNCTION OF AN INLINE BLENDER

TO RAPIDLY DISPERSE POLYMER PARTICLES CONTAINED IN A SLURRY INTO A JET FUEL STREAM AND DELIVER A HOMOGENEOUS SUSPENSION OF FINE POLYMER PARTICLES IN JET FUEL.

DISSOLUTION OF POLYMER PARTICLES IN JET FUEL IS A RELATIVELY SLOW PROCESS WITH A CHARACTERISTIC TIME MUCH LONGER THAN THE FLOW TIME THROUGH THE BLENDER.

STIRRING OF SUSPENSION AIDS DISSOLUTION PROCESS. SEVERE AGITATION DEGRADES POLYMER ALREADY DISSOLVED.

jpj →

- o PRODUCTION OF AMK AT REFINERIES FOLLOWED BY TRANSFER TO AIRPORT STORAGE FACILITIES AND SUPPLY TO AIRCRAFT FUELING STATIONS NOT FEASIBLE.
- o EXTENSIVE MODIFICATIONS TO AIRPORT FACILITIES NEEDED
- o UNINTENTIONAL DEGRADATION
- o EXPOSURE TO WATER
- o FILTRATION PROBLEMS
- o STORAGE LIFE
- o INLINE BLENDING AT AIRCRAFT FUELING STATIONS MOST PRACTICAL APPROACH.
- o BLENDED FUEL MUST ATTAIN ACCEPTABLE MIST SUPPRESSION AND DEGRADATION PROPERTIES WITHIN 15-30 MINUTES AFTER BLENDING.



- o POLYMER PARTICLE SIZE IMPORTANT IN DETERMINING WHETHER HOMOGENEOUS AMK WILL RESULT.
- o LARGE POLYMER PARTICLES IN A SUSPENSION SETTLE AT THE TANK BOTTOM. RESULTING AMK HAS LESS THAN DESIRED POLYMER CONCENTRATION. STICKY GEL FORMS AT TANK BOTTOM.
- o FOR A FIXED POLYMER TO GLYCOL WEIGHT RATIO SLURRY CHARACTERISTICS CHANGE FROM FREE FLOWING TO PASTE AS PARTICLE SIZE REDUCED.
- o DECREASE POLYMER LOADING TO RETAIN FREE FLOWING CHARACTER OF SLURRY USING FINE PARTICLES.



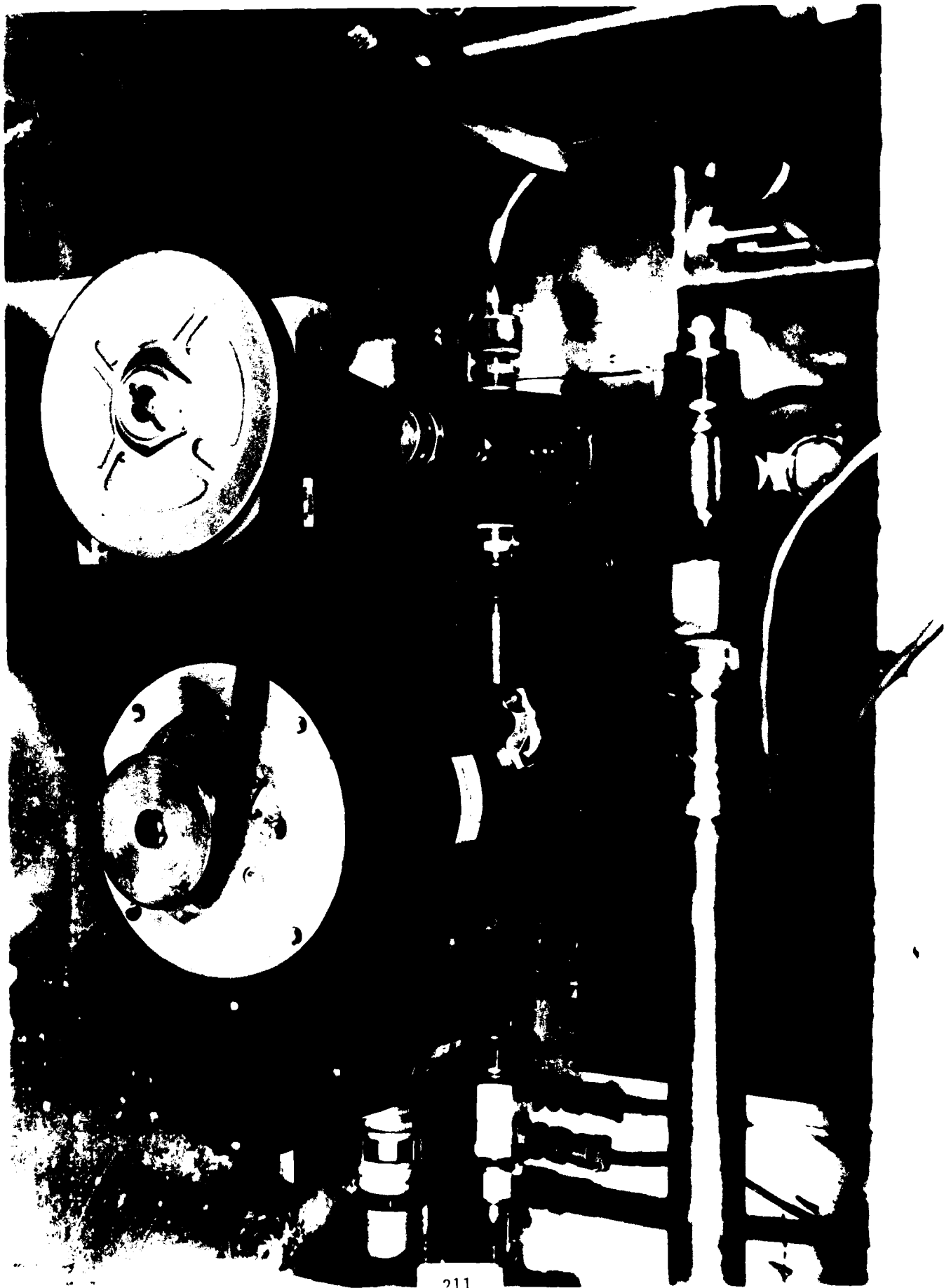
## BLENDER SUBSYSTEMS

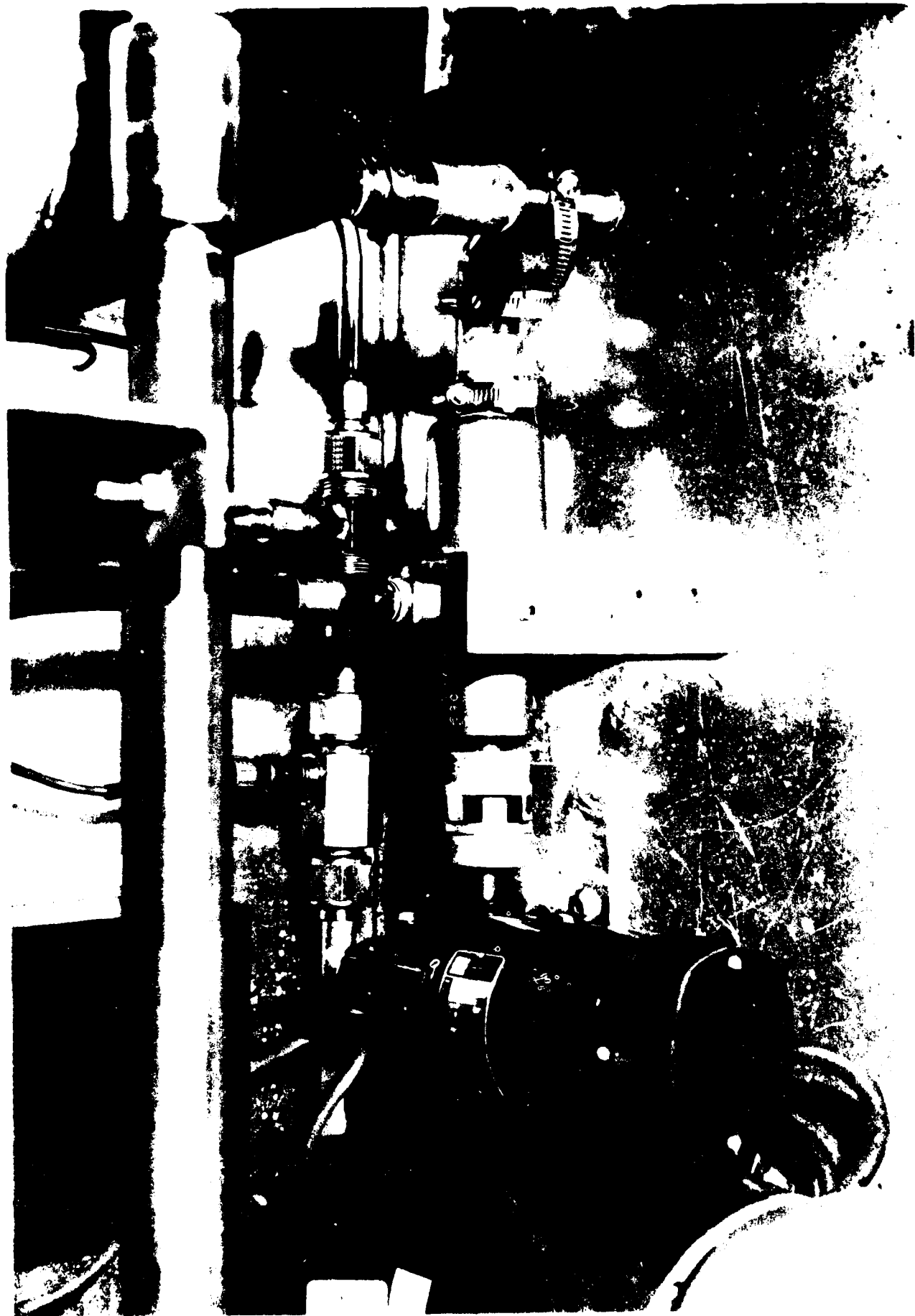
- 1) JET A PUMPING AND METERING SYSTEM
- 2) SLURRY PUMPING AND METERING SYSTEMS
- 3) MIXING DEVICE TO DISPERSE POLYMER SLURRY IN THE JET-A STREAM.



## COMPONENT SELECTION

- 1) GEAR PUMP FOR PUMPING JET A
  - o PROVIDES SMOOTH, CONTINUOUS FLOW
  - o FLOW RATE RELATIVELY INSENSITIVE TO SUPPLY AND DELIVERY PRESSURE FLUCTUATIONS.
  - o FLOW RATE ADJUSTED BY SPEED CONTROLLED D.C MOTOR
  - o TURBINE FLOW METER TO MONITOR JET A FLOW RATE
- 2) PROGRESSIVE CAVITY ROTARY SCREW PUMP FOR SLURRY PUMPING
  - o DESIGNED TO HANDLE SLURRIES WITH VISCOSITIES UP TO 100,000 CP.
  - o SPEED CONTROLLED D.C MOTOR DRIVE WITH 20:1 REDUCTION
  - o SLURRY FLOW RATE CALIBRATED AS A FUNCTION OF MOTOR SPEED AND DELIVERY PRESSURE.
- 3) STATIC MIXER
  - o RAPIDLY DISPERSES POLYMER PARTICLES INTO JET A STREAM
  - o NO ROTATING PARTS.
  - o SMALL PRESSURE DROP.





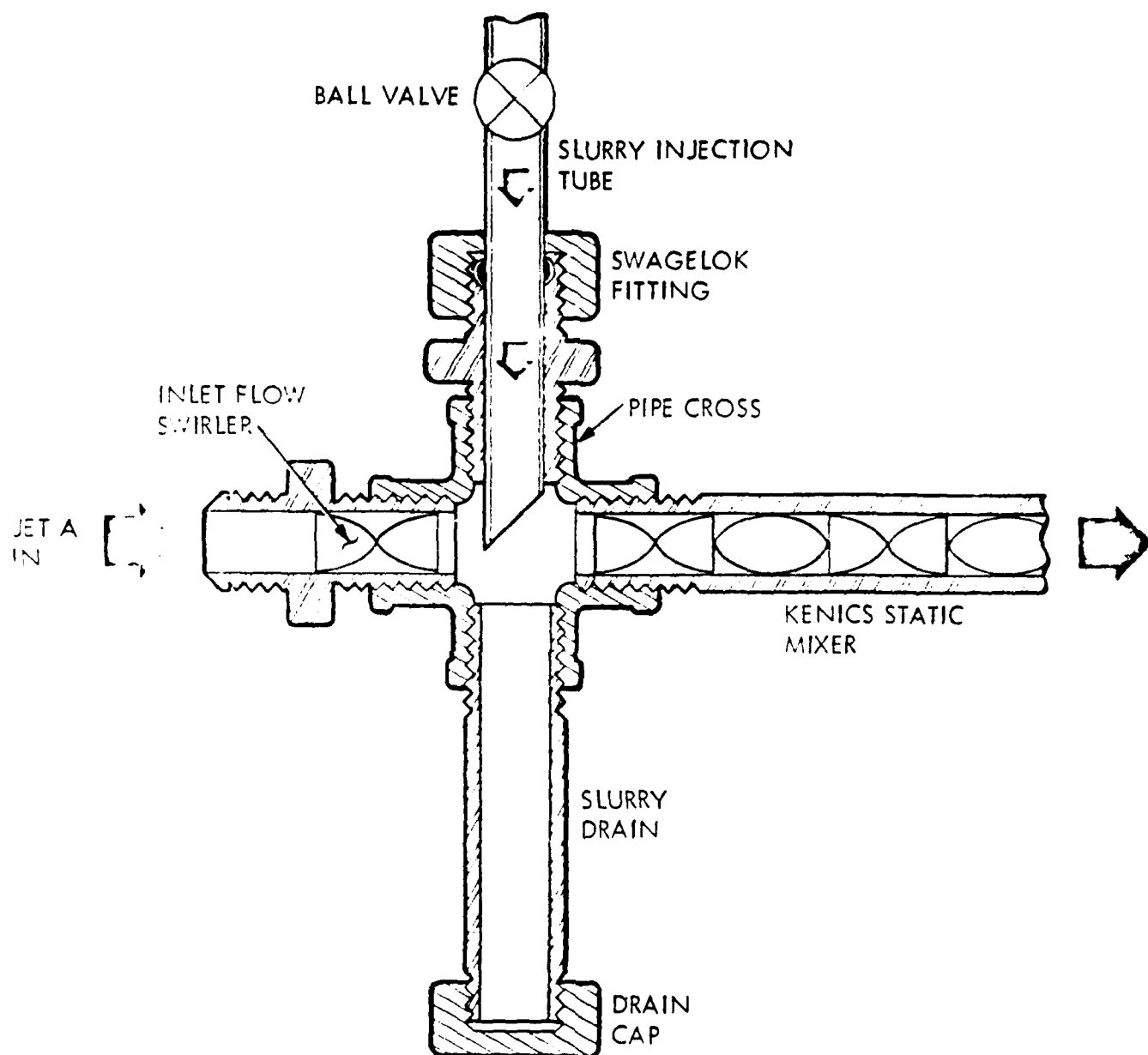


Figure 4 Details of slurry injection and dispersion scheme

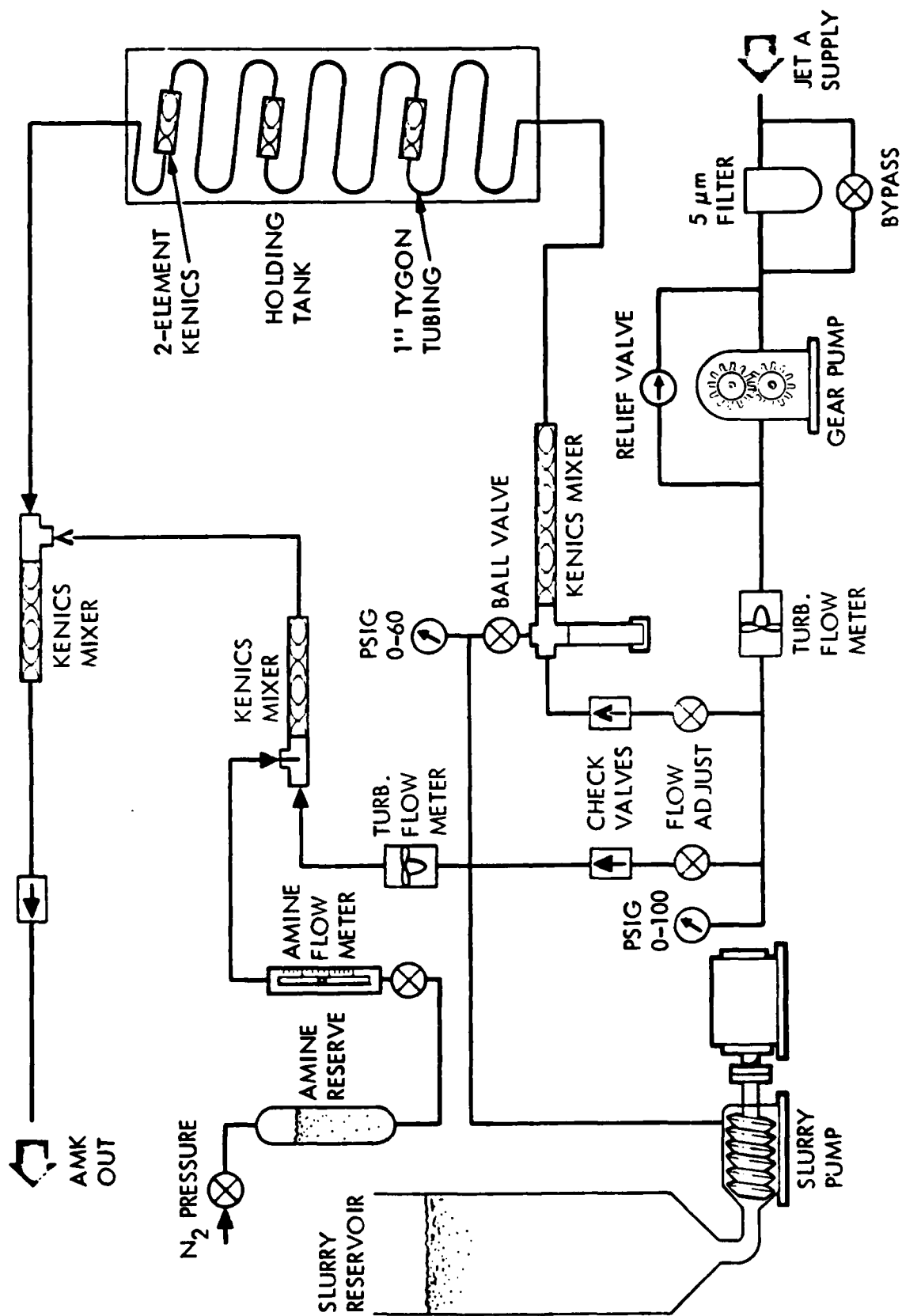
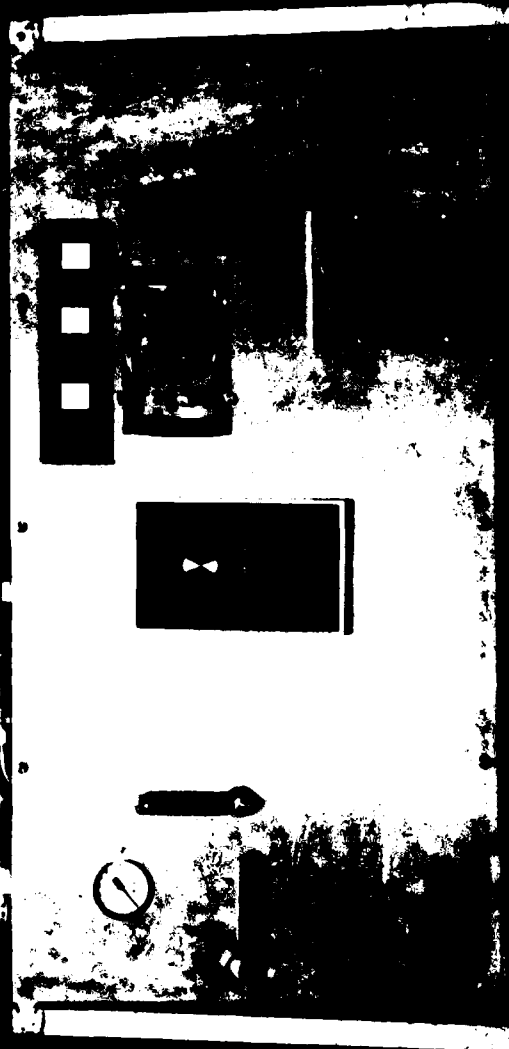
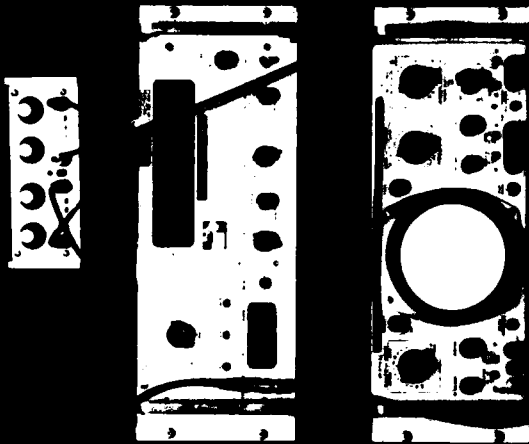
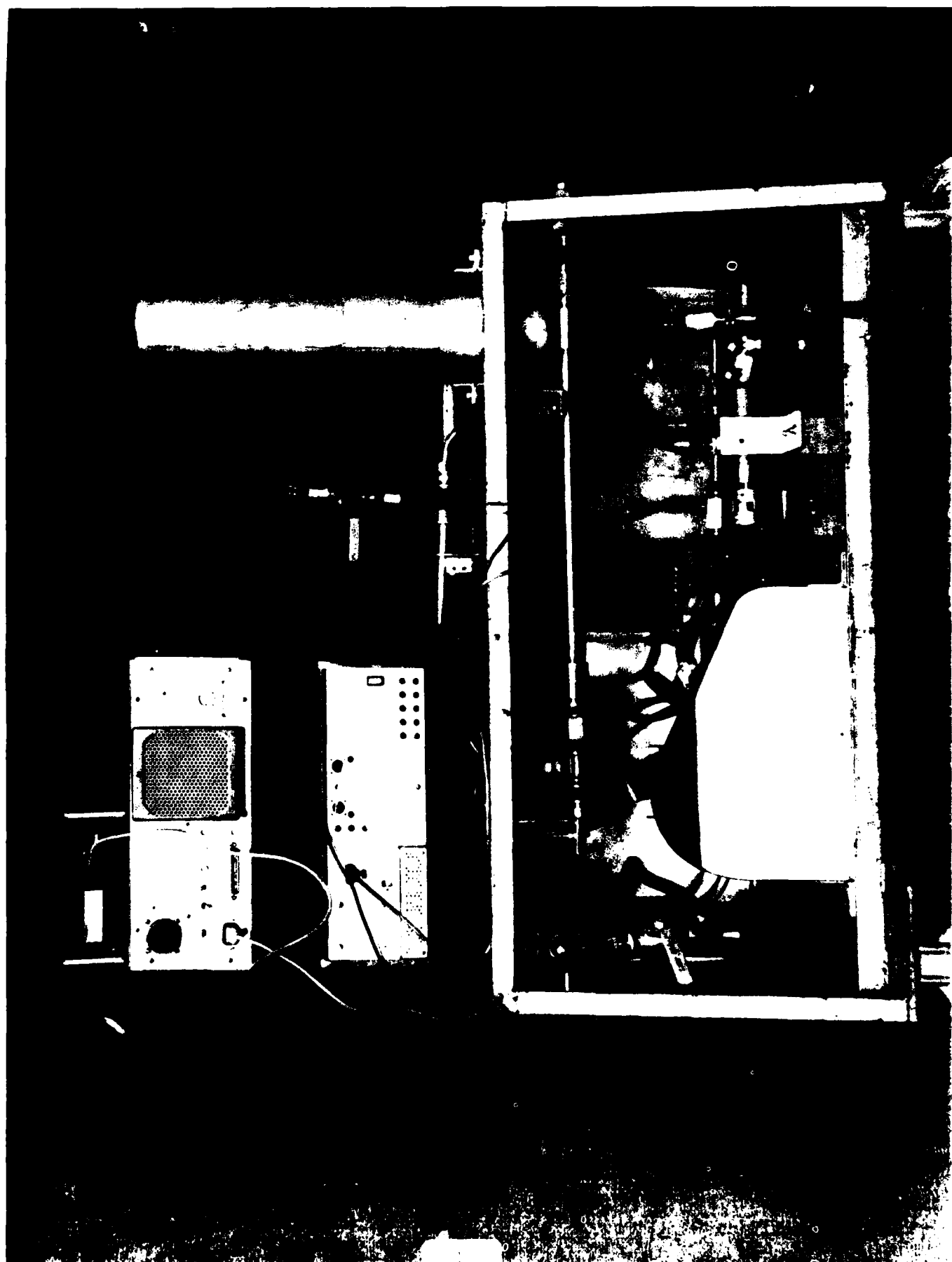


Figure 5 Schematic of the Inline Blender System







### CONCLUSIONS

- o A 10 GPM CAPACITY AMK INLINE BLENDER WAS SUCCESSFULLY DEVELOPED TO BLEND ICI SLURRIES OF FM-9 POLYMER WITH A METERED JET A STREAM USING A STATIC MIXER.
- o THE DESIRED POLYMER CONCENTRATION IN BLENDED AMK COULD BE ACHIEVED WITH  $\pm 6$  PERCENT ACCURACY.
- o THE BLENDED AMK ACHIEVED ACCEPTABLE MIST SUPPRESSION AND DEGRADATION PROPERTIES WITHIN 15 TO 30 MINUTES AFTER BLENDING.

SESSION III: FUELS RESEARCH - INDUSTRY

Chairperson: Dr. Alan E. Zengel

# OLEFIN POLYMERS AS JET FUEL ANTIMIST ADDITIVES

by

Steven L. Baxter, Conoco  
John M. Iwasyk, E. I. du Pont de Nemours and Company

## BACKGROUND

Olefin polymers have been extensively studied at Conoco for the past twenty years. In the course of these studies it was found that the combination of high MW and solubility in hydrocarbons allow these materials to dramatically affect the rheology of various hydrocarbon fluids, even at ppm treatment levels. Examples of potential applications of this technology include the reduction of pipeline turbulence (i.e., drag reduction) and mist control in spraying jet fuel<sup>1-3</sup>.

Conoco research in antimisting jet fuel began in the early 1970's with a testing program at the Southwest Research Institute (SWRI). That initial work was conducted on an additive designated AM-1<sup>4</sup>. AM-1 imparted what was at that time good antimist performance to the fuel. Successful tests were conducted with the FAA and various military agencies. However, additional research indicated that AM-1 also imparted unacceptable viscoelastic properties which rendered the fuel incompatible with existing aircraft fuel handling systems.

## ANTIMISTING ACTIVITY OF ULTRA-HIGH MW POLYMERS

Continued research at Conoco has yielded ultra-high molecular weight, oil soluble polymers which may have improved potential as antimist additives. This line of research has been followed with the expectation that higher performance materials could be used at lower treatment levels, thus minimizing the negative impact on other critical fuel properties.

The antimist performance of these second generation products (designated AM-2) has been evaluated on the FAA's Flammability Comparison Test Apparatus (FCTA) and on the larger scale Wing Spillage Test (WST). The FCTA is a device developed by FAA researchers for qualitatively screening antimist additives<sup>5</sup>. Fuel is introduced into an air stream which carries the atomized fuel past an ignition device. Two criteria are used in the evaluations, a pass/marginal/fail visual classification by the FCTA operator, and maximum heat output of the flame measured by calorimetry. Fuel and air flow rates are varied to generate flammability results over a range of conditions.

FCTA evaluations have been performed on two second generation products designated AM-2A and AM-2B, and for comparison purposes, on a sample of AM-1. AM-2A is the result of early efforts to improve product performance by changing polymer composition. Composition changes included increasing molecular weight and altering molecular weight

distribution. AM-2B is an even higher performance material obtained in more recent studies. Representative data are given in Tables 1-3. AM-1 was evaluated at a treatment level of 3000 ppm. AM-2A and AM-2B were evaluated at 1000 ppm because of their improved effectiveness.

Comparative data from Tables 1 and 3 (AM-1 vs. AM-2B) are presented in Figure 1 and show that AM-2B is roughly three times as effective as AM-1 in flame reduction on the FCTA. This conclusion is based on the observation that 1000 ppm of AM-2B gave essentially the same flame suppression as obtained with 3000 ppm of AM-1. AM-2A at 1000 ppm was not as effective as AM-2B. These observations correlate with the molecular weight of the polymers which range from AM-1 at the low end to AM-2B at the high end. This correlation between molecular weight and antimist performance has been suggested by other researchers.

The highest performance product, AM-2B, was further evaluated in the FAA's Wing Spill Test. The WST facility was designed to more accurately simulate the fuel release in a crash situation. The facility is described in detail in Report No. FAA-CT-81-11. The essential features include fuel spillage from the leading edge of a simulated wing while air flows past the spillage point and into the vicinity of an ignition source.

Table 4 summarizes the WST results obtained with AM-2B. No testing was done with comparison materials. However, results from FAA tests on other products suggest that treatment levels of up to 3000 ppm are required to equal the antimist performance of 1250 ppm AM-2B.

#### MIST DROPLET SIZE MEASUREMENTS

Studies of the effects of antimisting polyolefins on aerosol droplet size have also been conducted. The particle size distribution of treated jet fuel mists have been measured and compared to untreated fuel mist. Jet A fuel containing 0-500 ppm of AM-1, AM-2A, and AM-2B was tested.

The equipment used was a Particle Measuring Systems, Inc. (PMS) analyzer, which was available at the DuPont Engineering Technology Laboratory. This device has the capability of measuring droplet number and diameter in the range of 20-1240 microns. A schematic of the equipment is contained in Figure 2. The spray was generated with a flat fan hydraulic spraying systems nozzle type 800067.

The following conclusions emerge from the results of this testing:

- All of the additives significantly reduce the concentration of fines (particles of diameter less than 100 microns) in the spray.

- The arithmetic mean particle diameter of treated jet fuel increases with increasing additive concentration.
- AM-2B not only lowers the weight percent and number percent of fines, but also raises the mass flux in the center of the jet. This means that the spray jet plume is probably reduced in diameter.
- The effectiveness of these three additives in the reduction of fines and modification of mean particle diameter correlates with their performance in FCTA and WST evaluations.

The effect on fines concentration and mean particle diameter is particularly noteworthy. Figure 3 demonstrates the effect on fines concentration. With 500 ppm AM-2B, fines are reduced from 27.1% to 1.1%. Figure 3 also contains data obtained with AM-1. While the reduction of fines is significant, it can clearly be seen that the effectiveness of AM-1 is much less than AM-2B.

Figure 4 illustrates the effects of these additives on mean particle diameter. Again, all of the additives generate the same effect of increasing particle diameter. It is also evident from Figure 4 that the second generation products have a much greater impact at a given treatment level. At 500 ppm, for example, AM-2B has more than doubled the mean diameter while AM-1 has increased the diameter by about 30%.

This work makes no attempt to simulate the wind shear break-up of a jet fuel spill. However, these results do suggest a plausible mechanism for the control of flammability by antimisting polyolefins. This observed effect of the additives on mean particle diameter is consistent with results obtained at the Jet Propulsion Laboratory with a system designed to simulate jet fuel break-up with wind shear<sup>8</sup>.

#### IMPACT ON OTHER FUEL PROPERTIES

As mentioned above, earlier trials with AM-1 were discontinued because of seemingly insurmountable problems associated with handling the treated fuel. Conoco's initial approach to solving these problems has been to minimize the additive concentration by developing more active materials, and thereby maintain acceptable mist control while minimizing handling problems. The FCTA and WST results given above suggest that AM-2A and AM-2B may indeed represent a significant improvement in performance over AM-1. The next phase of Conoco's program is to evaluate the handling properties of jet fuel treated with AM-2 at these lower levels.

Table 5 summarizes the key areas of concern with respect to handling problems. Conoco is currently building a low temperature pumpability test device to evaluate treated fuels in this critical area.

The hydrocarbon nature of the polymer provides advantages in dissolution and low temperature compatibility (i.e., phase separation, reaction with moisture). Also, other research with high molecular weight polymers has shown that the higher molecular weight and lower concentration will simplify the intentional degradation required for efficient combustion. Lower concentrations of polymer will also minimize the effects on jet fuel heat transfer characteristics.

#### CONCLUSION

Flammability screening tests do suggest that higher molecular weight polymers can provide equivalent fire protection at reduced treatment levels. These reduced levels offer the potential advantages of decreased cost for the program and improved handling characteristics. This improvement in flammability protection is very possibly a result of the ability of these polymers to increase mean particle diameter and significantly reduce the concentration of fines. Future research will be directed toward evaluations of the handling properties of treated jet fuel as well as the preparation of even higher molecular weight (and hopefully more effective) additives.

TABLE 1  
FCTA RESULTS FOR AM-1, 3000 PPM<sup>a</sup>

Air Flow (m/s)	Fuel Flow (ml/s)			
	12	14	16	18
50	P(0.275)	P(0.371)	P(0.426)	P(0.522)
60	P(0.385)	P(0.495)	P(0.604)	P(0.604)
70	P(0.962)	P(0.948)	P(0.989)	P(0.536)

<sup>a</sup>Results are given as P=pass, M=marginal, and F=fail, with maximum heat output (Btu/ft<sup>2</sup>-sec) in parentheses.

TABLE 2  
FCTA RESULTS FOR AM-2A, 1000 PPM<sup>a</sup>

Air Flow (m/s)	Fuel Flow (ml/s)				
	10	12	14	16	18
40	P(0.027)	P(0.220)	P(0.165)	P(0.192)	P(0.261)
50	P(0.330)	P(0.440)	P(0.522)	M(0.604)	M(0.522)
60	P(0.385)	M(0.604)	M(0.673)	M(0.756)	M(0.838)
70	P(0.343)	P(0.646)	P(0.701)	P(0.728)	M(0.824)

<sup>a</sup>Results are given as P=pass, M=marginal, and F=fail, with maximum heat output (Btu/ft<sup>2</sup>-sec) in parentheses.

TABLE 3  
FCTA RESULTS FOR AM-2B, 1000 PPM<sup>a</sup>

<u>Air Flow (m/s)</u>	<u>Fuel Flow (ml/s)</u>			
	<u>12</u>	<u>14</u>	<u>16</u>	<u>18</u>
50	P(0.220)	P(0.302)	P(0.398)	P(0.440)
60	P(0.340)	P(0.440)	P(0.522)	P(0.550)
70	P(0.330)	P(0.357)	P(0.495)	P(0.522)

<sup>a</sup>Results are given as P=pass, M=marginal, and F=fail, with maximum heat output (Btu/Ft<sup>2</sup>-sec) in parentheses.

TABLE 4  
WING SPILLAGE TEST RESULTS WITH AM-2B

<u>Concentration (ppm)</u>	<u>Wind Velocity (knots)</u>	<u>Performance</u>
1000	110	Pass
1000	120	Pass/Marginal
1000	130	Fail
1250	120	Pass
1250	130	Marginal
1250	140	Fail
1500	130	Pass
1500	140	Marginal/Fail
1500	140	Pass

TABLE 5  
HANDLING PROBLEMS ASSOCIATED WITH TREATED FUEL

Low Temperature Pumpability  
Heat Transfer  
Degradability for Combustion  
Unintentional Degradation  
Low Temperature Compatibility  
Dissolution in Jet Fuel

### Footnotes

1. Lescarboua, J.A., Culter, J.D., and Wahl, H.A., "Drag Reduction with a Polymeric Additive in Crude Oil Pipelines," Soc. Pet. Eng. J. (Sept., 1971) 229-235.
2. Chao, K.K., Child, C.A., Grens II, E.A., and Williams, M.C., "Antimisting Action of Polymeric Additives in Jet Fuels," AIChE J., 30, 111-120 (1984).
3. Ting, R.Y., and Hunston, D.L., "Polymeric Additives as Flow Regulators," Ind. Eng. Chem. Prod. Res. Dev., 162, 129-136 (1977).
4. Weatherford, Jr., W.D., Fodor, G.E., Naegle, D.W., Owens, E.C., Wright, B.R., Schaeckel, F.W., "Development of Army Fire-Resistant Diesel Fuel," U.S. Army Fuels and Lubricants Research Laboratory Interim Report AFLRL No. 111, Southwest Research Institute, San Antonio, TX (1979)
5. Klueg, E.P., "Flammability Comparison Test Apparatus," in Conference Proceedings, Aircraft Research and Technology for Antimisting Kerosene Conference, FAA Report No. FAA-CT-81-181, (1981)
6. Hoyt, J.W., Taylor, J.J., and Altman, R.L., "Drag Reduction -- Jet Breakup Correlation with Kerosene-based Additives", J. Rheology, 24, 685-699 (1980)
7. Salmon, R.F., "Wing Spillage Tests Using Antimisting Fuel," FAA Report No. FAA-CT-81-11, (1981)
8. Fleeter, R., Petersen, R.A., Toaz, R.D., Jakub, A., and Sarohia, V., "Antimisting Kerosene Atomization and Flammability," FAA Report No. DOT/FAA/CT-82/19, (1982)

# OLEFIN POLYMERS

-SOLUBILITY IN HYDROCARBONS

-HIGH MOLECULAR WEIGHT

-APPLICATIONS

Drag Reduction

Mist Control

AM-1

-GOOD PERFORMANCE

-FUEL HANDLING DIFFICULTIES

## SECOND GENERATION PRODUCTS

- HIGHER PERFORMANCE

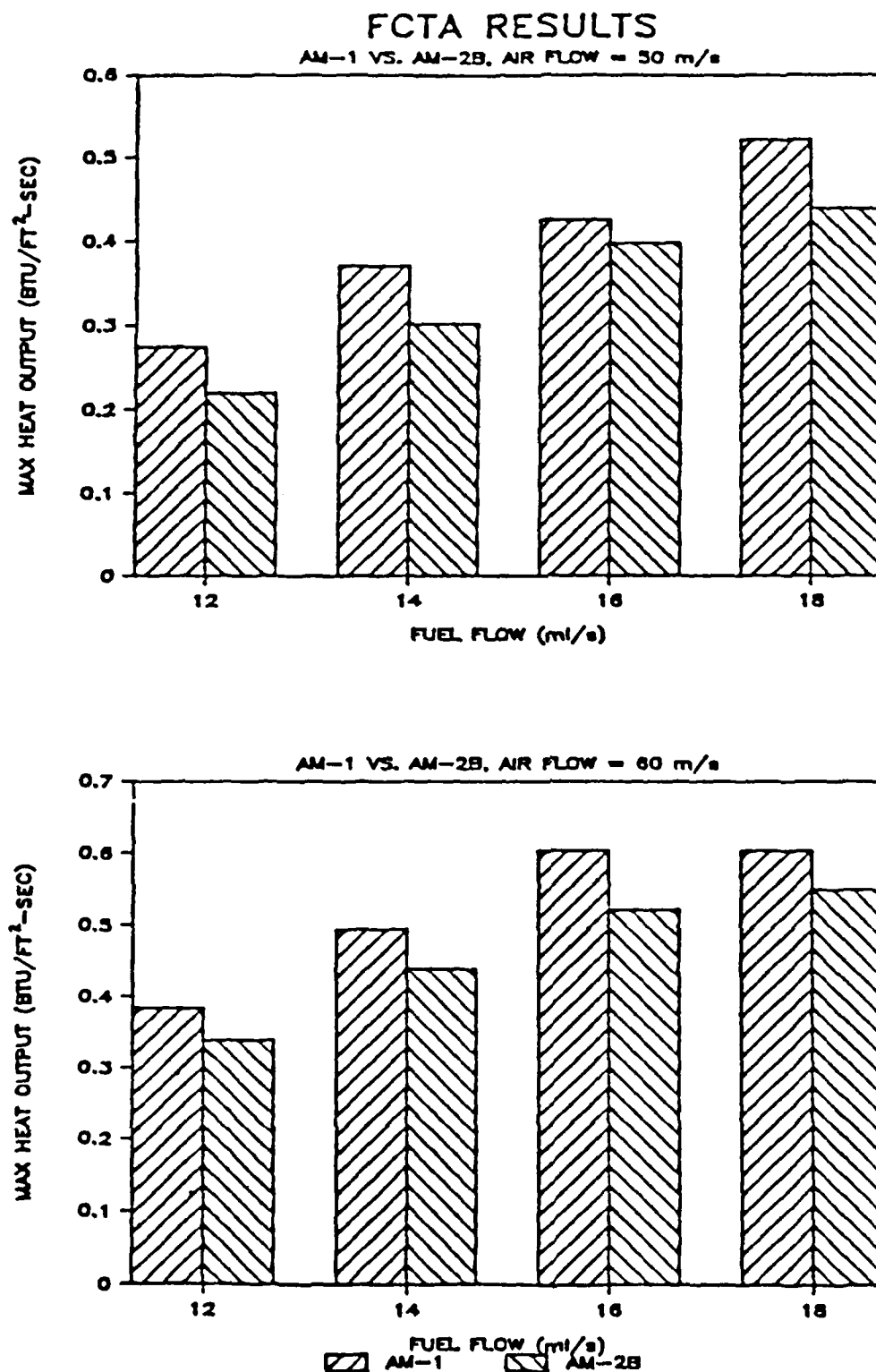
- LOWER USE LEVELS

- MINIMAL IMPACT ON FUEL PROPERTIES

- AM-2A

- AM-2B

FIGURE 1  
MAXIMUM HEAT OUTPUT OF AM-1 (3000 PPM)  
AND AM-2B (1000 PPM) TREATED FUEL

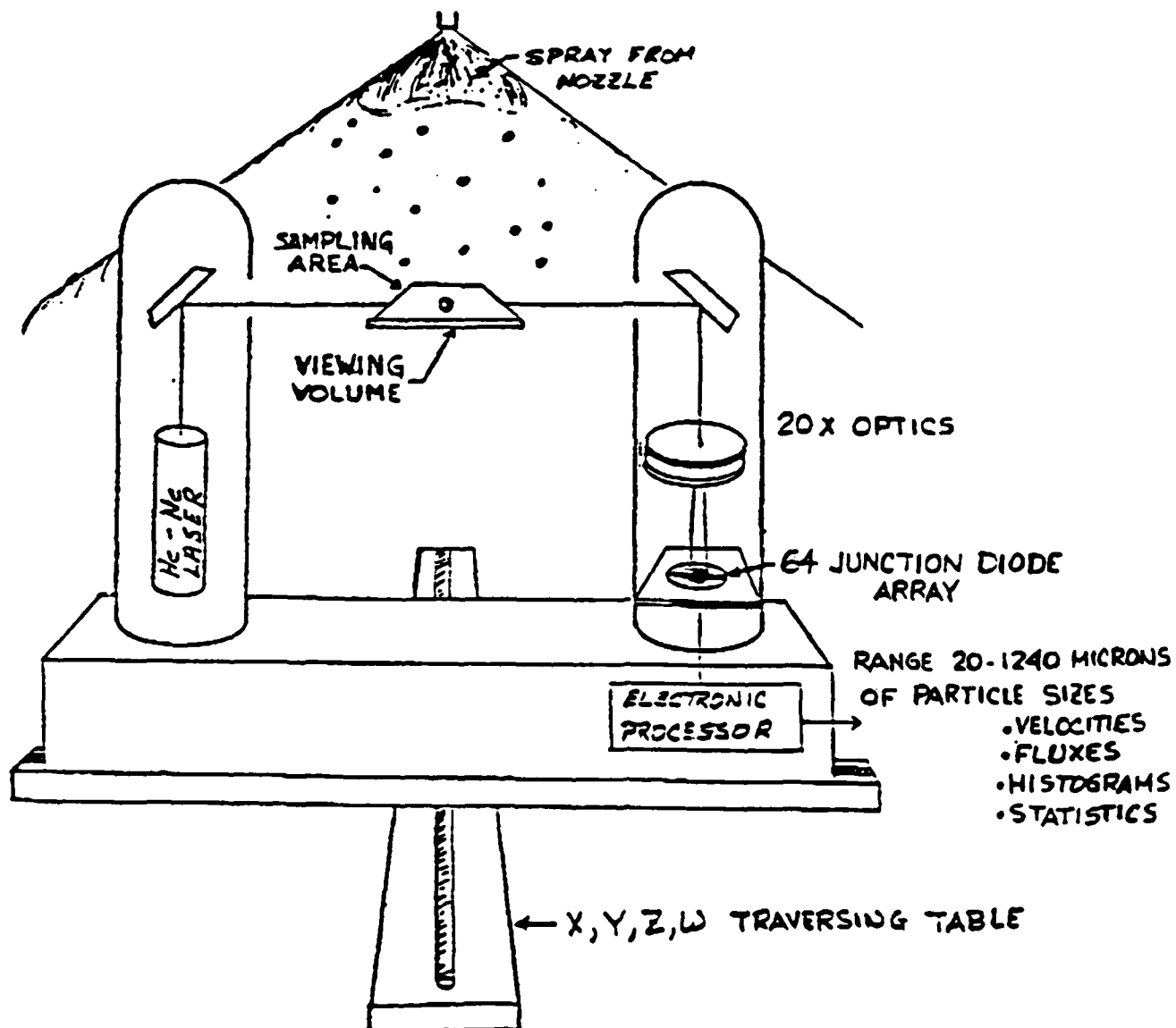


# WING SPILLAGE TESTS

AM-2B

PPM	KNOTS	RANKING
1000	110	+
	120	+ / 0
	130	-
1250	120	+
	130	0
	140	-
1500	130	+
	140	0 / -
	140	+

FIGURE 2  
 PARTICLE MEASURING SYSTEMS ANALYZER  
 FOR MIST DROPLET SIZE MEASUREMENTS



*PMS 2D PROBE*

FIGURE 3  
PERCENT FINES (<100 MICRONS) IN MIST  
AT VARIOUS TREATMENT LEVELS

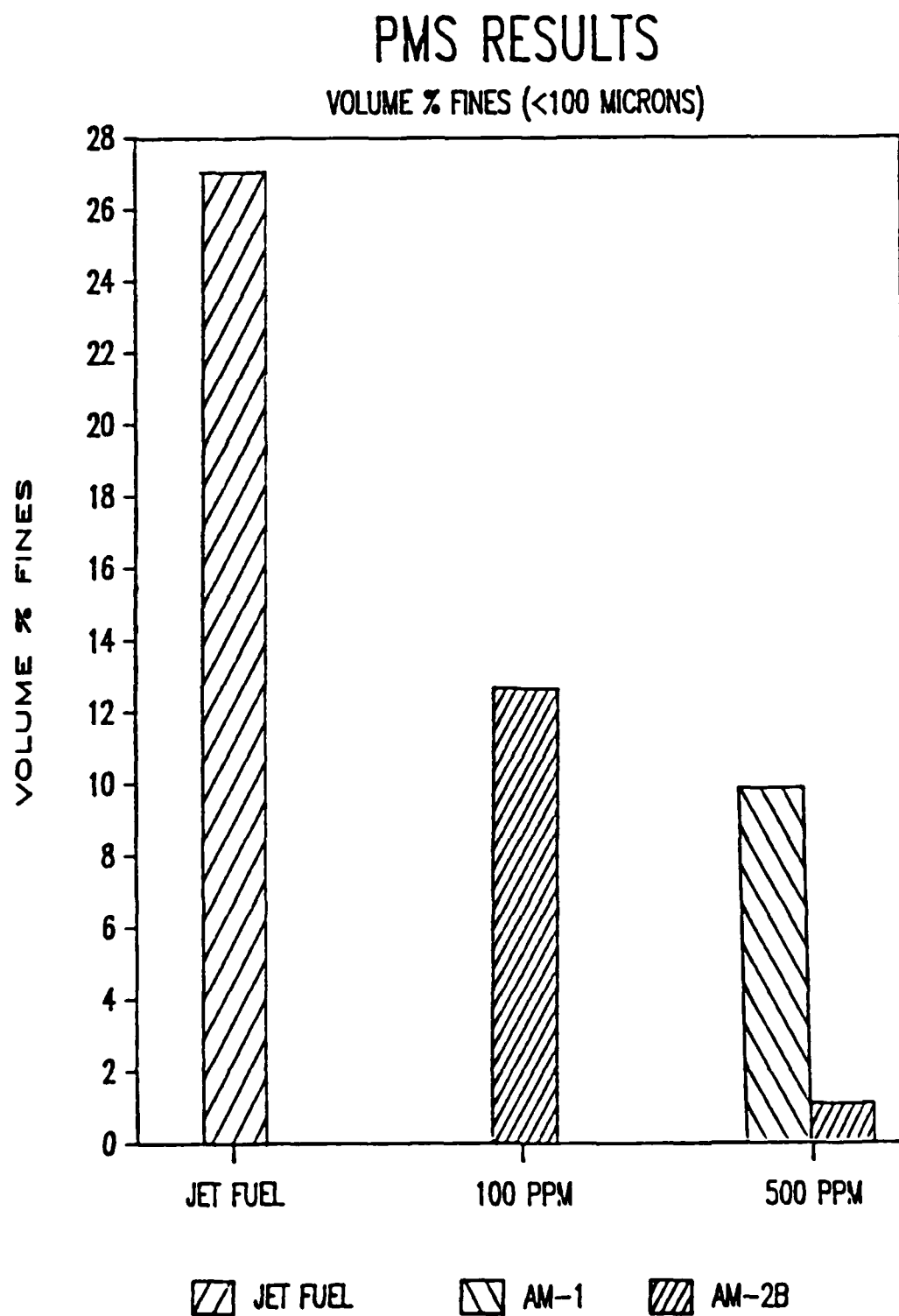
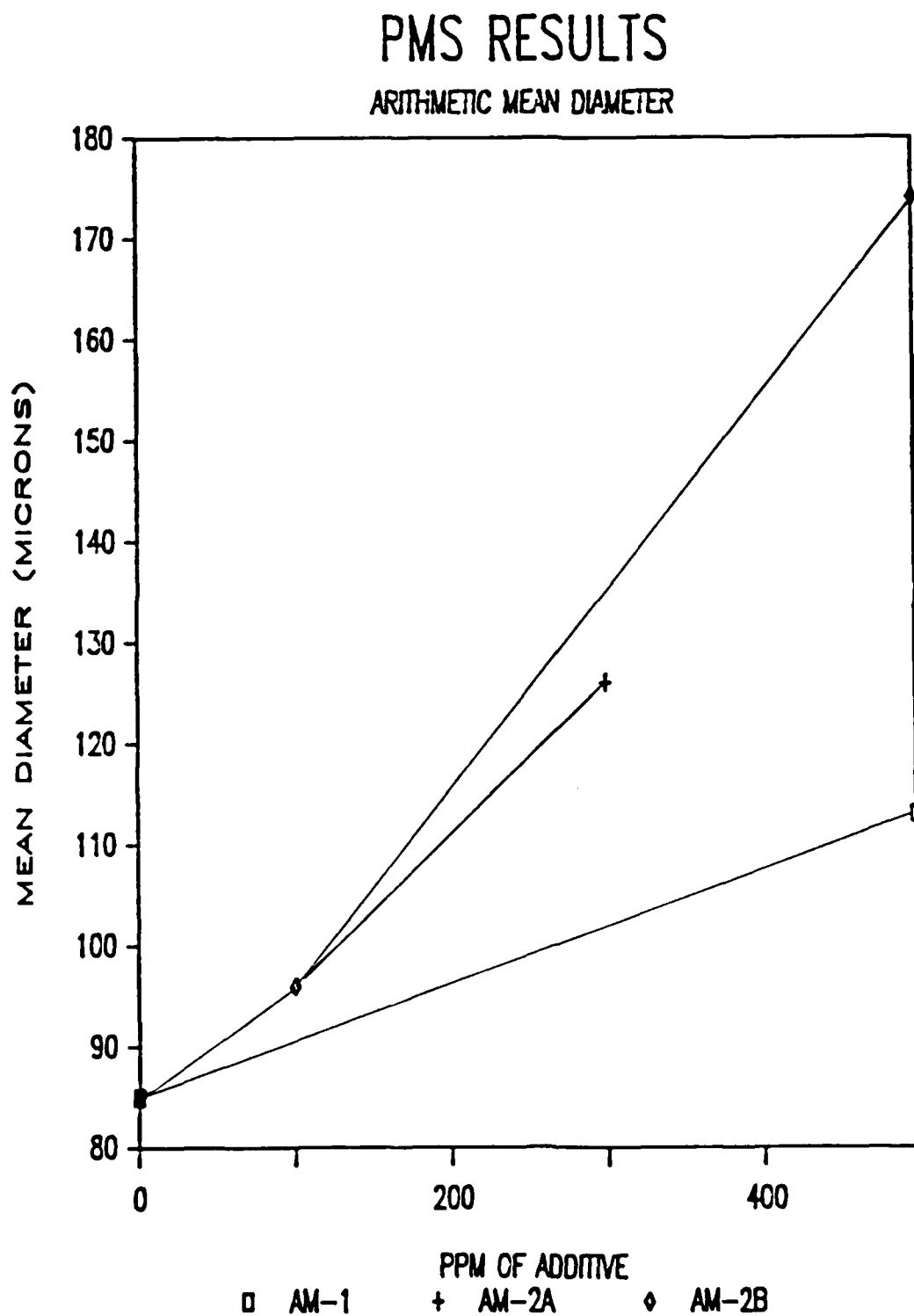


FIGURE 4  
ARITHMETIC MEAN DIAMETER OF MIST DROPLETS  
AT VARIOUS TREATMENT LEVELS



# HANDLING PROBLEMS ASSOCIATED WITH TREATED FUEL

- LOW TEMPERATURE PUMPABILITY
- HEAT TRANSFER
- DEGRADABILITY FOR COMBUSTION
- UNINTENTIONAL DEGRADATION
- LOW TEMPERATURE COMPATIBILITY
- DISSOLUTION IN JET FUEL

## CONCLUSIONS

- HIGHER MW POLYMERS GIVE EQUAL PROTECTION AT REDUCED LEVELS
- POTENTIAL IMPROVEMENTS IN FUEL HANDLING PROPERTIES
- OLEFIN POLYMERS INCREASE MIST DROPLET SIZE AND REDUCE FINES

AMK - STILL VIABLE?

PAPER PRESENTED BY CHARLES G. RIVERS, JR.

AMK TECHNICAL MANAGER

ICI AMERICAS INC.

## AMK - STILL VIABLE?

Good afternoon, The question posed in the title of my presentation is one which a great many people--including those in the councils of ICI--have been asking since last December 1. There is no question the immediate reaction to the CID was dismay; but as scientific people, we recognized the need to analyze the events of the CID and to understand the causes. FAA has done a very thorough job of this in the past ten months. In the next ten minutes, I would like to add ICI's views on the AMK program and where we believe it should go from here.

First, what are FM-9 and AVGARD? FM-9 is a high molecular weight polymer and is the active ingredient in AMK. However, it exists in powder form; and along with the obvious handling and measuring difficulties, it does not readily dissolve in jet fuel. Therefore, we slurry the polymer with a carrier fluid consisting of a glycol and an amine to make AVGARD slurry. This is the product we supply to FAA. Anti-misting kerosene is jet fuel containing approximately 1% AVGARD slurry.

In developing this additive over a number of years (beginning with FM-3), we strove to meet a number of technical "targets." First and foremost, of course, is fire suppression. As I will discuss later, and as FAA has already stated, there is a considerable body of evidence that suggests that AMK can greatly reduce fire risk. Secondly, the additive must dissolve readily in jet fuel to minimize fueling turnaround. Third, it should be degradable so that AMK can be used as an aircraft fuel. Fourth, the modified fuel must retain good fluid properties over the entire operating temperature range of jet aircraft fuel. For dissolved polymers, this specifically means low temperature pumpability. Fifth, the additive--AVGARD-- must be both stable in storage yet sufficiently fluid to handle in the field for blending. And, finally, no additional problems, such as corrosive components, can be introduced.

The additive for the CID did not fully meet these technical goals--it contained sodium and the dissolution rate was marginal against the 15-20 minute "target." We have produced laboratory quantities of sodium-free FM-9 with improved dissolution and can modify our production process accordingly to produce such a product.

What then is the status of the AMK program? How much do we know and how much more do we need to find out? The answer to both is -- a lot.

### 1. Does AMK "Work"?

By this I mean: Is AMK effective in suppressing post-crash fires? From the outset, ICI's approach has been to minimize misting of kerosene spilled from ruptured tanks,

which is generally accepted as a key factor in creation of post-crash fireballs. AMK repeatedly demonstrated its effectiveness in tests over 17 years, including ground-based crash tests of redundant aircraft. This repeated success resulted in an outside impression that AMK was somehow "fireproof."

However, anti-misting kerosene is, after all, 99% kerosene; and fuel misting is not the only factor in post-crash fires. This was highlighted by the CID where fire resulted from factors other than spilled fuel misting.

We fully support FAA's recommendation that what needs to be done now is to define the "envelope" where anti-misting is effective and relate that to actual crash history. FAA has already begun, and work to date suggests that anti-misting would be beneficial in a high proportion of impact-survivable crashes--CID notwithstanding.

Finally, a very significant observation at CID, subsequently demonstrated at JPL and reinforced by recent FAA tests as described by Mr. Westfield, is that AMK burns at a slower rate with the result that unburned fuel may arrive at the impinged surface in liquid form, providing a cooling effect.

## 2. Is AMK "Usable"?

Primarily because of its "degradability" requirement, it is a practical impossibility to pre-blend AMK (say, at a refinery) and store it in bulk for subsequent transfer to aircraft. The AVGARD additive must be accurately blended with jet fuel during fueling of an aircraft. This means separate storage and handling of the additive and operation of a precision blender during fueling.

These requirements mean that more hardware (blenders) and more human skills are required to fuel aircraft with AMK as opposed to jet fuel. From our standpoint as supplier of the additive, we must formulate AVGARD to be compatible with in-line blending and have good long-term storage stability. Our production slurry is fluid and chemically stable, but we have not yet entirely solved the tendency of the slurry to separate on standing.

FAA has developed continuous prototype blenders of ever-increasing capacity, and two of the large units were used to fuel the CID aircraft. Blender development appears to be well in hand.

Existing technology appears adequate to prevent inadvertent introduction of bulk water during blending; but because of the sensitivity of AMK to bulk water, additional safeguards are required to guarantee that technology is always applied.

### 3. Is AMK "Safe"?

AMK is different from jet fuel. From the start it has been mandatory that substitution of AMK for jet fuel not compromise the integrity and reliability of aircraft fuel systems which have been developed over the years. It is in this area of operability/reliability that the greatest testing effort remains to be done.

On the positive side, the limited work to date suggests few, if any, problems during "normal" operation. Bench-scale tests have shown that AMK has adequate low temperature pumpability and that "normal" moisture ingress (during simulated flight) causes no problem. Approximately 100 engine-hours, both on test stands and in-flight, have been accumulated without any engine failure. Prototype degraders have demonstrated that mechanical degradation is feasible. And, finally, one aspect of the CID, which was overshadowed by the end result, was that for the first time, an aircraft took off and flew powered entirely by AMK.

A number of potential problems still remain. In early engine trials, hard gel accumulated on fuel filters. This phenomenon disappeared with continued use of AMK leading to the conclusion that the gel was nucleated by dirt particles which were eventually removed by AMK's detergent action. This needs to be proved and understood.

Another potential gel-related problem occurs when AMK is mixed with kerosene. This gel is transitory, and empirical means (such as addition of AMK carrier fluid to the kerosene) have been found to prevent it. Nevertheless, the phenomenon is not fully understood.

Earlier I mentioned that the AVGARD supplied for CID contained sodium (equivalent to 35 ppm in the AMK). We have long accepted that sodium and other alkali metals are unacceptable for prolonged engine use, and we have developed a sodium-free FM-9 which FAA has tested and pronounced equivalent in performance to "production" FM-9.

Numerous other tests have identified differences between AMK and jet fuel, the significance of which needs to be defined. Specifically, AMK has:

1. Better lubricity.
2. Lower heat transfer coefficients in heat exchangers.
3. Better thermal stability.
4. Lower pumping efficiencies.

The greatest need in the area of operability is extended engine testing. While work to date is encouraging, no single run has been more than a few hours. Extended tests would go a long way toward answering some of the present concerns.

Where, then, do we believe the AMK program should go from here? There is no question that as a demonstration of fire suppression, the CID was unsuccessful. Notwithstanding this, we endorse FAA's stated belief that a large majority of impact survivable crashes with post-crash fires would be mitigated by the use of AMK.

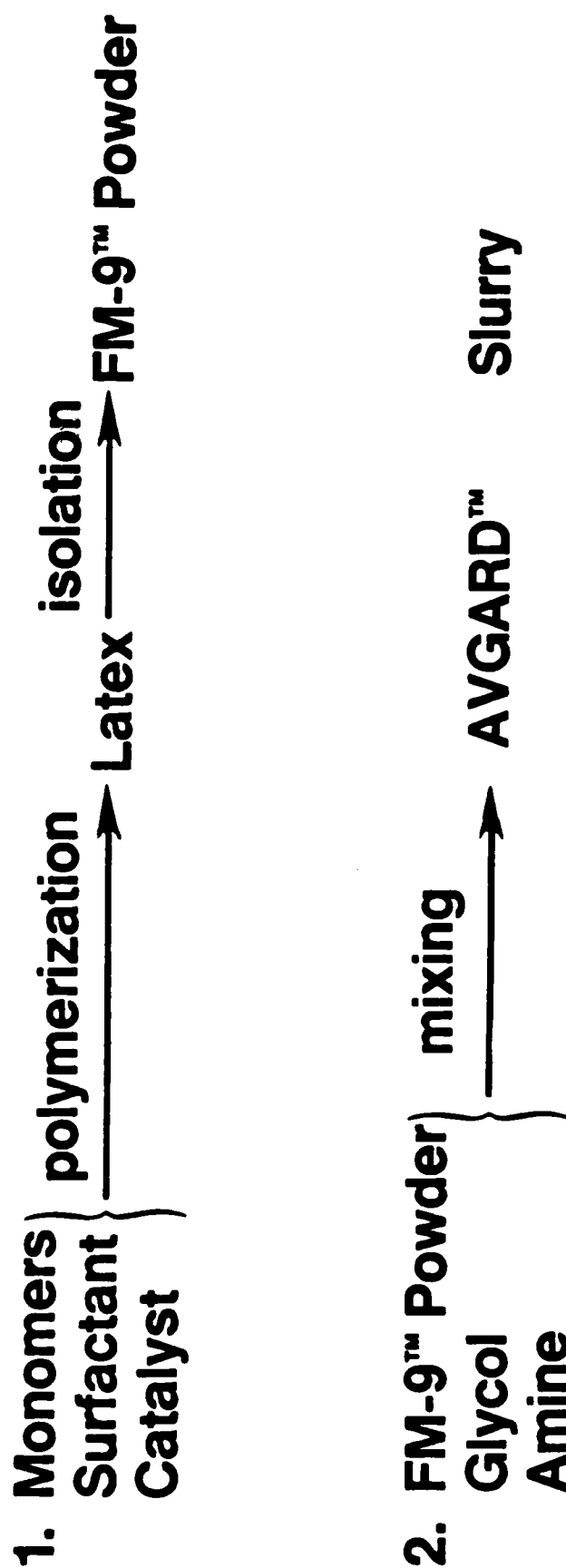
Although AMK is clearly not the total solution to post-crash fires, we believe it is a valuable, and indeed necessary, tool. We recognize that the program must be led and must be implemented by FAA; and we are prepared to follow their lead by supplying product, developing process and product improvements (including "new" polymers), and scaling up production when called for.

In summary, we believe that AMK is, indeed, still viable and that the results of the CID, regardless of the visual impact of the television films, should not negate a very promising program. We strongly urge that FAA actively continue to define AMK's fire safety "envelope" and proceed to assess its operability in aircraft. Thank you, and may I answer any questions?

CGR:jye  
10/29/85

091885JYE04

# FM-9™/AVGARD™ PROCESS



# **Requirements**

- Fire Suppression
- 10-15 Minute Dissolution
- Degradable
- Low Temperature Pumpability
- Stable, Fluid Slurry
- Free of Corrosive Components

# DOES AMK “WORK”?

# IS AMK "USABLE"?

**IS AMK "SAFE"?**

## AIRLINE VIEWS ON SAFETY FUELS

Presented at  
Federal Aviation Administration Fuel Safety  
Fuel Safety Research Workshop  
October 30, 1985

By

A. R. Tobiason  
Assistant Director Engineering-Safety Technology  
Air Transport Association

On behalf of the Air Transport Association of America and its member airlines, thank you for the opportunity to appear at this conference to state our views on fuel safety research. My name is Dick Tobiason, Assistant Director Engineering, Safety Technology for the ATA.

First, a little background on who we are. ATA, which was founded in 1936, represents 31 U.S. airlines, and in 1984 its members operated over 85% of the U.S. scheduled flights and carried almost 90% of U.S. revenue passengers. Domestic ATA members operate 2500 passenger aircraft of fifteen fundamentally designs offered by eight airframe manufacturers. Another 400 aircraft are operated by parcel carriers and canadian associate members.

Over the years ATA member airlines have supported numerous FAA safety objectives to reduce the threat of post-crash fire hazards to aircraft occupants. ATA and airline support included memberships on the SAFER Committee, which made recommendations in 1980 to the FAA Administrator on the post-crash fire aspects of cabin materials and Anti-Misting Kerosene (AMK). Many of the FAA fire safety programs address aircraft hardening such as fireblocked seats, cabin/cargo bay materials, smoke detection, extinguishers, emergency lighting, and AMK. With the exception of AMK, many of these programs have been or will be implemented by the airlines over the next several years and because of their practicality, they should improve safety even though the post-crash fire threat is an extremely rare event. These programs should not in themselves cause a degradation in safety or as some would call it, impose a down-side risk. The statistics for post-crash fire fatalities averaged over many years indicate that about 30 fire fatalities per year represents the United States' experience, compare this to 4200 fire fatalities and 19,000 fire injuries per year in residential buildings.

Fuel safety considerations began with the realization that jet fuel represents the largest source of post-crash combustible materials. Spilled fuel fires are involved in a significant percentage of post-crash accidents and are the dominant initiating mechanism for aircraft cabin and cargo bay materials. AMK represents the most recent government-industry effort to eliminate or reduce post-crash fires.

The AMK concept, the third in a series of R and D efforts over the last 20 years, represents the closest technology has come to a solution. Unlike the programs mentioned earlier, AMK could have significant potential to reduce safety under non-accident conditions and such a possibility is unacceptable.

The FAA apparently agrees with this potential. As reported by FAA to Congress early this fall, the AMK failure mode in last year's Controlled Impact Demonstration and yet-to-be resolved technical and operational problems caused the FAA to cease rulemaking on AMK. In support of this conclusion, Administrator Engen stated that progress was being made by prompt rulemaking to address the use of improved flame resistant cabin materials, fire extinguishers, smoke detectors and emergency lighting in the U.S. airline fleet.

ATA is concerned about the balance between jet fuel "Hardening" and accident prevention. For example, in today's congressional testimony (to the Aviation Subcommittee chaired by Mr. Mineta) on wind shear, Boeing indicates that during the last ten years nearly half of all fatalities resulting from U.S. commercial aircraft accidents during takeoff and landing occurred with wind shear identified as a contributing factor. Post-crash fires were involved in a majority of these cases and some were not survivable. A great deal of cooperative government and industry work is in progress to prevent flight in conditions conducive to wind shear with FAA planning to spend large sums on ground-based facilities and equipment to remotely detect and communicate the nature of the hazard to aircrews. ATA has supported this accident prevention approach through the use of Terminal Doppler Radar and airborne remote detection research for windshear avoidance.

ATA believes that this type of accident prevention as well as the benefits for aircraft fire hardening must be included by the FAA in its economic analyses to determine which safety R&D programs should be pursued in support of potential rulemaking. This is particularly appropriate when R and D funds are scarce. We note with interest the following FAA statement in the October 10, 1985 notice of proposed rulemaking on protective breathing equipment (PBE):

The FAA has carefully evaluated the cost and benefits to this proposal and has concluded that the lives saved are in addition to any lives that have previously been accounted for in other cabin safety initiatives.

A number of NASA and FAA contracted cost-benefit studies determined that FM9 AMK was not cost-beneficial. These studies generally agreed that the estimated costs were several times the benefits. An interesting minimum cost estimate for each 1% additional cost of AMK fuel over Jet A fuel amounts to about \$100 million each year that the airlines would have to pay. Following the PBE example, the estimated AMK benefits would be significantly less than earlier postulated. These economic studies should be updated immediately to determine under what conditions or constraints AMK would be cost-effective.

In parallel, the FAA should conclude technical work on AMK within a reasonable short period to determine if the undesirable AMK characteristics can be eliminated by further modifications to FM-9, or alternative additives.

If this turns out to be unsuccessful, then the books should be closed on AMK.

We also must realize that in the transition from AVGAS to kerosene-based fuels, most of the technical unknowns were uncovered through military experience before commercial operations began. We do not have the luxury of that experience in the case of AMK safety fuels nor are we likely to gain it since DOD is not involved at present.

Ideally, any fuel additive that would suppress post-crash fires should require the same type of quality control measures used in today's fuels. Several airline and aircraft manufacturing representatives at this conference will be able to discuss the quality control aspect in more detail within the working groups. ATA member airlines are concerned about the maintenance of high quality control standards for today's jet fuels to the degree that ATA has formed a Fuel Quality Task Force. The Task Force is now completing an ATA specification in this area. Also, attending this workshop are several ATA member airlines who are members of SAE, ASTM and Coordinating Research Council organizations dealing with aviation fuel quality.

We believe this workshop will be useful in bringing everyone up-to-date on AMK, revisiting past alternative approaches and laying the groundwork for the future. During the working group discussions we should also review all of the SAFER recommendations relating to fuel safety. We are open to new ideas that would provide safe, practical and economic solutions.

## **SAFETY FUELS — SPECIFICATIONS AND PROGRESS**

by

**A. T. Peacock**

**McDonnell Douglas Corporation  
Douglas Aircraft Company  
Long Beach, California**

### **ABSTRACT**

The need for a standard technical description of aviation turbine fuels that are developed to enhance fuel safety is discussed. Fuel property descriptions, test methods, and standardization procedures are also discussed, along with approvals for additives and fuel quality control. The role of ASTM in standardization is outlined, and a short history of safety fuels is given. It is suggested that fuel modification should not be abandoned as a method of improving safety.

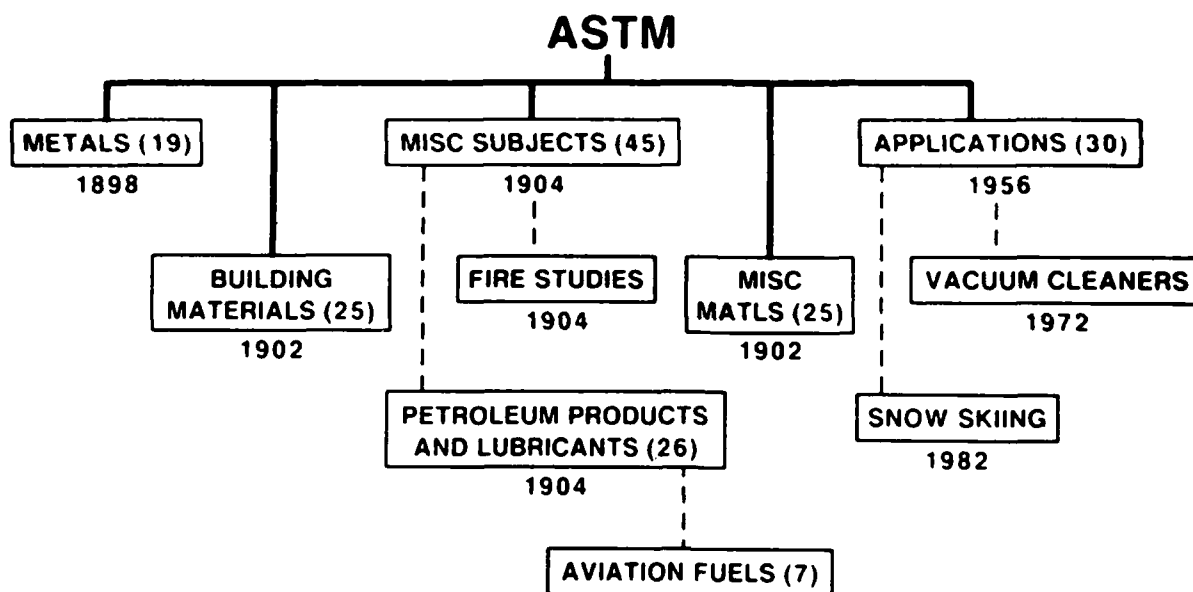
This paper discusses fuel standardization and quality control and the mechanisms already in place to attain them. It reflects on 20 years of development of safety fuels and considers where the Federal Aviation Administration (FAA) should go from here.

We must have standards to live by in our daily progression through life and commerce to give some reasonable expectations of what the other person may be doing or is going to do. The rules and customs of commerce may be less familiar than the rules of vehicular traffic flow but they serve the same purpose.

### **AMERICAN SOCIETY FOR TESTING & MATERIALS**

The American Society for Testing & Materials (ASTM) is composed of interested people representing companies, agencies, or themselves who work together to establish a consensus on standards for commerce covering many of the things you see and use every day.

Figure 1 presents an abbreviated view of the ASTM's diverse coverage. One first-level committee, D2, whose work is described in Figure 2, covers the products of petroleum — the wonderful energy source that is easy to process, transport, and use, and contains so many BTUs per pound while occupying a small volume. Subcommittee J (S/C J) on Aviation Fuels is part of D2. This subcommittee's area of effort is outlined in Figure 3.



NOTE: THE DATES GIVEN IN THIS CHART REPRESENT THE YEAR THE EARLIEST COMMITTEE WAS FORMED FOR EACH SUBJECT. THE NUMBER OF COMMITTEES IS SHOWN IN PARENTHESES.

**FIGURE 1. ASTM COMMITTEES**

S/C J establishes and maintains standards for both aviation turbine fuels and aviation gasolines. Sections of S/C J cover many aspects of fuel and fuel handling. Any time there is a need for a standard in aviation fuels, Subcommittee J of ASTM Committee D2 will establish that standard. There are also several task forces and panels that focus on specific subjects.

It should be noted that ASTM's resources come from participating companies, agencies, and people. These resources are limited and are available only when these groups are interested in the result. The groups practice an amazing amount of philanthropy for the greater good; but the reality of the balance sheet shows up more and more, even in good times, and affects the support of the ASTM, even by America's top grossing companies.

We need general standards such as ASTM D-1655, the recognized standard for aviation turbine fuels. Under D-1655, there are more specific standards; for example, a test method to determine fuel heating value with established limits. An accepted standard like this assures everyone involved in air transport that all other parties involved are following the same rules. If an airline needs to have a certain amount of energy on board at takeoff, that energy must be in a form compatible with the aircraft and the route to be flown. The energy cannot be bound in shale rock, even if that might offer an advantage in fuel fire safety.

**GASOLINE**  
**AUTOMOTIVE LUBRICANTS**  
**BURNER, DIESEL, TURBINE FUEL OILS**  
**LUBRICATING GREASES**  
**LIQUIFIED PETROLEUM GASES**  
**AVIATION FUELS**  
**HYDRAULIC FLUIDS**  
**RECYCLED PRODUCTS**  
**RESEARCH DIVISIONS (13)**

**FIGURE 2. PETROLEUM PRODUCTS AND LUBRICANTS COMMITTEE**

**TURBINE FUEL SPECIFICATION (D-1655)**  
**GASOLINE SPECIFICATION (D-910)**  
**COMBUSTION CHARACTERISTICS**  
**HIGH-TEMPERATURE STABILITY**  
**CLEANLINESS**  
**ELECTRICAL CHARACTERISTICS**  
**TASK FORCES AND SPECIAL PANELS**

**FIGURE 3. AVIATION FUELS SUBCOMMITTEE**

### **FUEL PROPERTIES**

To have standards, what is to be standardized must be known. Accordingly, requirements have been established for aviation fuel properties, both physical (distillation and viscosity) and chemical (aromatic content or water reaction). The properties may be directly measured (freeze point) or they may be inferred from measurement standards at specific conditions, extrapolated on the basis of known variations in characteristics (specific gravity, viscosity). All the properties and variations in material characteristics must be known to an acceptable level of confidence. This common ground of understanding allows the producer to separate the raw materials and to process them as needed. Manufacturers of equipment can independently design a machine to utilize the fuel. The airline operator can count on not being surprised during aircraft operation. The fuel must be absolutely within specification.

The description of properties unique to safety fuels will be derived from tests conducted by the companies or agencies that develop the fuels. The description may be physical, chemical, or performance-related.

## **METHODS AND EQUIPMENT**

Many methods are used to maintain aviation fuel standards. Some methods were borrowed from other areas, while others were developed for use with aviation fuels as the need arose. And still others are new ways to measure traditional properties. When a need is established to measure a particular property, equipment to make the measurements will generally be developed by those with the interest, the capability, and the incentive. There is nothing like a monetary profit to provide an incentive. However, technical recognition is also a strong motivator.

Researchers will generally establish which properties are required of a fuel to establish a desirable characteristic. The antimisting kerosene (AMK) program indicated that elongational viscosity was a parameter of significance. An inspired FAA engineer, Tom Guastavino, patented a measurement method.

The equipment and procedures developed for property measurement must be repeatable and they must be reproducible, both within acceptable levels of tolerance. ASTM has well-established methods for standardization and for precision statement development.

## **FAA/ASTM COMMUNICATION**

A few years ago, the FAA asked ASTM about the development of methods and specifications in its evaluation of FM-9, an antimisting additive. ASTM reviewed the status of the program and replied that while its members are keenly interested in developments in safety fuels, at the time AMKs were not well-enough defined nor was there sufficient interest indicated by members to engage in a large-scale program. However, a task force was established and maintains contact with the FAA. Regular reports are made at the semi-annual ASTM meetings on the current status of AMK development, and anyone with a particular interest contacts the FAA directly. When the time comes, ASTM will be prepared to take on the tasks. The process will be formalized through proceedings that will follow ASTM guidelines in developing a consensus on standards. Again, the need for standard development must be established or at least be perceived to be established. Then, most of the people who were working on the development of AMK will also work on the ASTM standards for AMK because the society is composed of interested members of the aviation fuel industry working together to produce a consensus on standards.

## **FUEL ADDITIVES**

The current safety fuel concept, AMK, has been established using proprietary additives. FM-9, produced by Imperial Chemical Industries (ICI), is one example. It was selected by FAA as a vehicle for evaluation of the AMK concept and has been subjected to a long series

of tests. Any additive proposed for use with fuels must be evaluated for its compatibility with the other materials it will encounter in international use. These other materials include coatings and sealants to make tanks corrosion-proof as well as base materials for equipment. The additive must be compatible with any other additives used, whether for the same purpose or for a different purpose. The additive may impart certain properties to the fuel whereby system performance could be affected; for example, a change in the performance of a lubricity additive may affect fuel pump wear.

There are many manufacturers whose products must be checked and whose agreement must be obtained before an additive can be used. Fortunately, many materials are common to these manufacturers. Working under the ASTM, the industry has established procedures for evaluating fuel additives. These procedures are described in ASTM method D4054 and in Research Reports D02-1125 and D02-1137.

The additive supplier must obtain the approval of the fuel handlers and the equipment manufacturers before his additive is put into fuel in the marketplace.

### **QUALITY CONTROL**

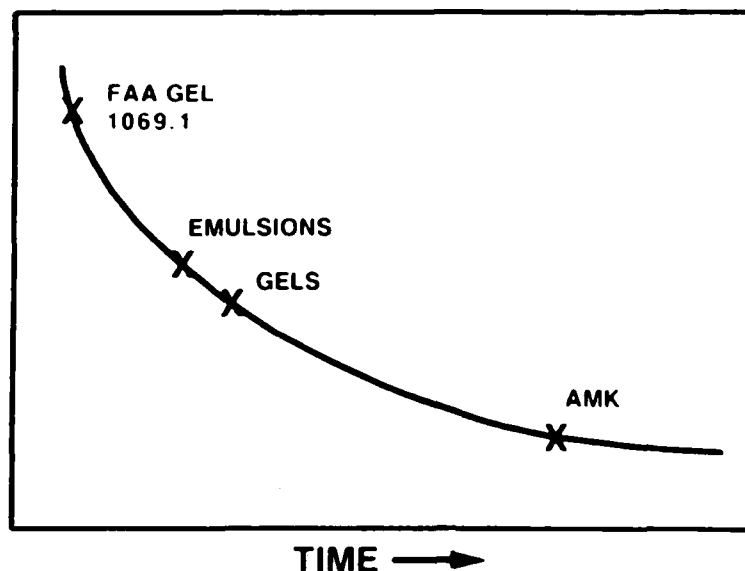
We must have safe fuel to do the primary job of flying. We want the highest quality we can get, as a practical matter. We provide that quality today by measuring the properties of the fuel at various stages from production to use. We filter out the dirt and separate out the free water; we do it again and then we do it again. We maintain the equipment and train the personnel who use it. We have excellent fuel today as a result of these practices.

We must make sure we have equally good quality control when we start using safety fuels. We have to compensate for the effect of any fuel additives on our quality control procedures. If we are inserting the additive during refueling, we must know the quality of the fuel *in the aircraft tank* because that quality level will determine the satisfactory performance of the aircraft in its routine operation, as well as the performance of the fuel if it must serve to improve fuel fire safety. It must be *believed* to be good enough for both jobs, but it must be *known* to be good enough for routine operation.

### **HISTORICAL PERSPECTIVE**

The FAA and the aviation fuel industry have been working on development of safety fuels off and on for many years. This work is briefly described in Figure 4. Early efforts concentrated on gels and evolved to include emulsions. FAA Gel 1069.1 was so stiff it would stand by itself. The high-phase-ratio emulsions developed later were markedly better and the gels of the mid-1960s were even better in some aspects. Today, we have the AMKs.

Every time the FAA and the industry put more effort into safety fuels, the fuels get better. The term "better" means different things to different people. Here, it refers to the fuel's overall performance and specifically its performance in contemporary aircraft fuel systems. It must be kept in mind that there are nearly 3,000 aircraft in the domestic turbine-



**FIGURE 4. SAFETY FUELS DEVELOPMENT HISTORY**

fuel-using fleet. These aircraft were all designed to use fuel with the properties standardized in D-1655, the ASTM turbine fuel specification. Any safety fuel would have to be reasonably compatible with the fuel systems of these aircraft in order to be economically viable. Compatibility with the ground system is required as well. Modifying the fuel is very attractive — it is attacking the fire problem at its root, it is always available, and it could be the least-penalty approach to improved fuel fire safety.

Units and scales have been omitted on the ordinate of Figure 4. From the system standpoint, the curve in the figure might be a plot of viscosity at a low shear rate and a low shear-stress level. The asymptote is the neat fuel property. Incidentally, the plot also shows the trend of fuel fire fatalities in commercial aviation, except the asymptote for that trend would be very near zero.

## **SUMMARY**

We must have standards. Industry has and will continue to cooperate with the FAA in further development of safety fuels. The ASTM, which *is the industry*, will assist in establishing specifications and in standardizing test methods for quality control of these fuels.

Fuel modification is an attractive way to attain the safety goals we all want. The FAA should not give up the safety fuels program because of an undesirable perception of the Controlled Impact Demonstration (CID) which was conducted by the FAA last December at Edwards Air Force Base. A full description of the CID will be presented in the record of the proceedings of this workshop.

**CURRENT DESIGN PROCEDURES  
FOR MINIMIZING POST CRASH FIRE HAZARDS**

**PRESENTED TO  
FAA FUEL SAFETY RESEARCH WORK SHOP**

**H. SKAVDAHL**

**OCTOBER 30, 1985**

## CURRENT DESIGN PROCEDURE FOR MINIMIZING POST CRASH FIRE HAZARDS

The presentation I have to make will give some background as to where we are today in both fuel system design and propulsion system installation relative to minimizing the post crash fuel fire hazard, how we got where we are, and will conclude with a few remarks on things to consider in future developments.

Current designs are a culmination of information learned in the past, starting with the first controlled flight by the Wright Brothers. Commercial airplane design requirements are, of necessity, in a continuous state of change. The reasons for changing requirements are various. Some are due to new technology that has been developed which requires new criteria. Others are due to a better understanding of the problem areas. One of the major contributors to the latter case is operational experience. As you well know, every commercial airplane incident or accident is thoroughly investigated for what went wrong and what can be done to prevent a reoccurrence. The nearly 30 years of commercial jet aircraft operation has taught the industry many lessons in airplane design. Through close cooperation of the FAA and industry, it has been possible to capitalize on the lessons learned. As a result, the safety of commercial airline passengers has continued to improve. One of the reasons for the continuing improvement in passenger safety is the emphasis which the FAA and the industry have placed on this subject. This workshop itself, sponsored by the FAA and supported by industry as well as the academia is evidence of the high priority placed on the continuing search for safety improvements.

The items to be discussed are representative of the industry although some companies may achieve the same objective by a different design method. Also the features discussed are representative of the most recent designs.

Before discussing the design features, I would like to briefly consider the nature of the problem. Three elements are necessary to produce fire conditions, these being 1, flammable material, 2, oxygen, and 3, an ignition source. Elimination of any one of these elements will prevent a fire. The item which the designer has the most control over is the ignition source. Therefore major emphasis is placed on eliminating actual or potential ignition sources to the greatest degree possible. In areas where the ignition source cannot be eliminated, for example the hot engine case, there are two schools of thought. One is to minimize the oxygen supply so that combustion cannot be supported. The other is to ventilate in sufficient quantities so that a combustible fuel-air mixture will not occur due to inadvertant fuel leaks. Either method has its pros and cons. The best method depends on the particular application. For crash situations, precautions are also taken to eliminate the fuel source. An example of this is the fuel shutoff valve as shown on Figure 1. When closed, this valve prevents fuel from going to the engine or if for example the engine/nacelle separates from the airplane, the shutoff valve prevents fuel from exiting the broken fuel line. In order to provide maximum capability of shutting this valve off under emergency conditions, the valve is located in a protected area of the airplane, typically on the wing spar. Wiring to the valve is duplicated and separated and two sources of actuation are provided, one by the fire handle and the other at the engine cutoff lever. The second actuation capability was provided as a result of an incident which occurred in London. In this particular incident the pilot activated the engine cutoff lever but did not activate the fire switch since the engine/nacelle departed the airplane and there was no indication of a fire. However, fuel was exiting the broken fuel line and a fire ensued which engulfed the airplane as it came to a stop. As a result of that incident the fuel shutoff valve is also activated by the engine cutoff lever, thus preventing a recurrence of this type of accident as well as providing a dual cutoff capability.

The drainage provisions for protection against lightning and ground fires are shown in Figure 2. Vents and drains are located well out of critical lightning strike zones. Streamering of attached lightning sweeping across the vent outlets is prevented by using flush type outlets which produce minimum field distortion. Flame arrestors are used in all vent and drain outlets to protect against flame propagation into fuel tanks during ground fires.

Figure 3 illustrates the design procedure used for fuel lines in pressurized compartments. In this case they are shrouded either by fuel resistant, rubberized fabric which is reinforced to take shroud pressure loads or by aluminum tubing. The shroud retains and drains any leakage that may occur in the fuel line. The shroud is also vented to ambient pressure to minimize vapor accumulation and limit shroud pressure. Also shown on Figure 3 is the separation of fuel lines and electrical wiring with the further precaution of routing fuel lines below wiring runs to ensure that any fuel leakage will not contact a potential ignition source of electrical components.

A typical installation of a body auxiliary fuel tank is shown in Figure 4. A primary consideration in selecting a location for body fuel tanks is that they are protected by other airplane structures in the event of a crash landing. These tanks are therefore located away from the path of collapsing landing gear and above major airplane load structures. All sump valves and plumbing are located above body frames. Fuel lines are shrouded and sufficiently flexible so that they will not separate except in the most severe crash conditions. Where fuel lines are routed through areas susceptible to damage during a crash, they are designed to be flexible enough to allow a reasonable degree of deformation and stretching without leakage. Typically, these are multi-component hoses of teflon, rubberized fabric and

braided metal cover. This fuel hose is designed to be highly impact resistant and is required to withstand the impact of a cutter blade at 120 knots with 12-inch deflection and no leakage. As in wing tank installations, body tanks must be properly vented and drained.

Safety features for pressure fueling operations are shown in Figure 5. Automatic fueling shutoff valves are used to prevent tank overfill and overboard fuel spillage. The vent system prevents excessive pressure buildup inside the tank. There have been incidents in the past of static discharge igniting the fuel during fueling operations. This problem has been resolved by improvements to filters in airport fueling facilities which result in lower static charge of fuel entering the airplane. In addition, charge density in the fuel tanks is minimized by use of multiple fueling discharge ports at the bottom of the tanks. This concept distributes the electrostatic charge of incoming fuel over a large tank surface area to minimize surface charge concentration and ensure benign relaxation of the charge. No fueling incidents due to static discharge have occurred since the incorporation of these design improvements.

An important structural design feature for impact situations is the strut breakaway design (Figure 6). All strut-to-wing interface attachment bolts are designed as single pin structural fuses. Local support structure in the wing has adequate margin of safety for the maximum fuse pin failure loads, including manufacturing tolerances and heat treatment variations. Hazardous loads therefore cannot be transmitted from the nacelle strut to the primary wing box structure prior to separation of the nacelle strut from the wing. Plumbing and electrical installations are designed so that wires and tubing will fail within the strut, thus preventing failures of these components within the wing box.

Additional propulsion system installation safety features are also shown in Figure 6. Firewalls are installed between the engine and strut to preclude fire penetration from the engine fire zones to strut and wing. Material selection is based on the ability of the firewall to prohibit fire penetration during exposure to a 2000°F fire for 15 minutes.

Engine bleed air used for airplane equipment cooling and wing anti-icing is precooled before distribution into the airplane to prevent unsafe temperatures in areas where flammable fluid components exist.

Great care is exercised in locating fuel system components on the engines to minimize the likelihood of component damage resulting in fuel leakage in the event of a wheels-up landing. In addition, where possible, fuel components are located on the engine to minimize any potential hazard from engine fragments in the event of a non-contained failure of the adjacent engine.

A number of fuel fire safety features, both for post crash situations and normal operations have been presented. Design for safety is a continuing educational process. Both industry and government continue to strive for improvement in all phases of flight operations. Crash prevention is the best solution for the post crash fire. However, until we totally achieve crash prevention, it is necessary to do the best job possible at reducing the post crash fire risk.

The airplane fuel system consists of a number of components and sub-systems as listed on Figure 7. Continued safe and reliable functioning of all these systems must be ensured with the introduction of any new component or system. For example, in the development of flame arrestors for use in fuel tank vents, a first consideration was protection against tank overpressure in the unlikely event that the flame arrestor might become blocked. The existence of a tank pressure relief valve in each surge tank

provided the necessary safety backup feature, thus allowing implementation of the flame arrestor concept.

Criteria which must be satisfied in the design of a new component or sub-system are listed on Figure 8. First, satisfactory operation must be provided over the complete operational envelope of the airplane, including both ground and flight operation. Generally, it is the envelope corners or end points that determine the basic design, i.e. the min and max operational temperature, highest operating altitude, etc. Fail-safe or redundant components are fundamental. The new system must be compatible with other systems. Any failure of the system must not require immediate action of the flight crew for continued safe operation of the airplane. If improved safety is the objective, then there must be reasonable assurance that the system is indeed working correctly. Current airplanes are operating with a dispatch reliability in excess of 98%. Clearly any new system must have an extremely high reliability to maintain today's standard and low maintenance cost must be a prime consideration.

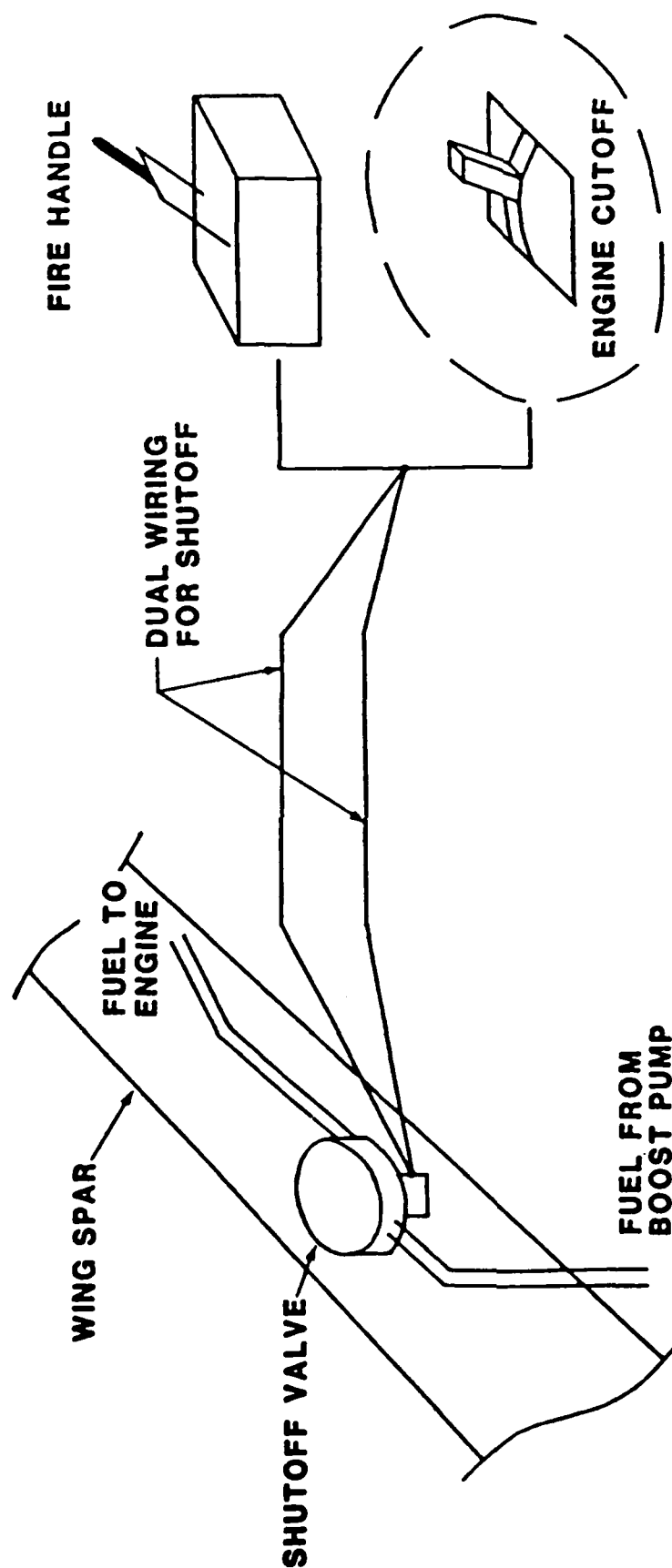
As a result of many years of both design and operational experience, a number of axioms for maximum safety have been developed. Some of these are listed in the final figure (Figure 9). Again, fail-safe design appears as a major axiom. Minimizing the number of components between the wing and engine reduces the number of places for potential fuel leaks. Using the fuel tank for fuel system tubing, connectors, and components wherever possible permits any potential fuel leakage to be returned directly to the tank without hazard. Maximum crash protection is provided for items which are required to be external to the tank by locating them above or adjacent to major airplane structure.

**FIG. 8 DESIGN CRITERIA FOR NEW COMPONENT OR SYSTEM**

---

- OPERATIONAL CAPABILITY OVER COMPLETE AIRPLANE  
OPERATING ENVELOPE
- FAIL-SAFE OR REDUNDANT
- COMPATIBLE WITH OTHER SYSTEMS
- OPERATIONAL VERIFICATION
- HIGH RELIABILITY
- LOW COST MAINTENANCE

**FIG. 1 FUEL FEED SHUTOFF (SPAR VALVE)**



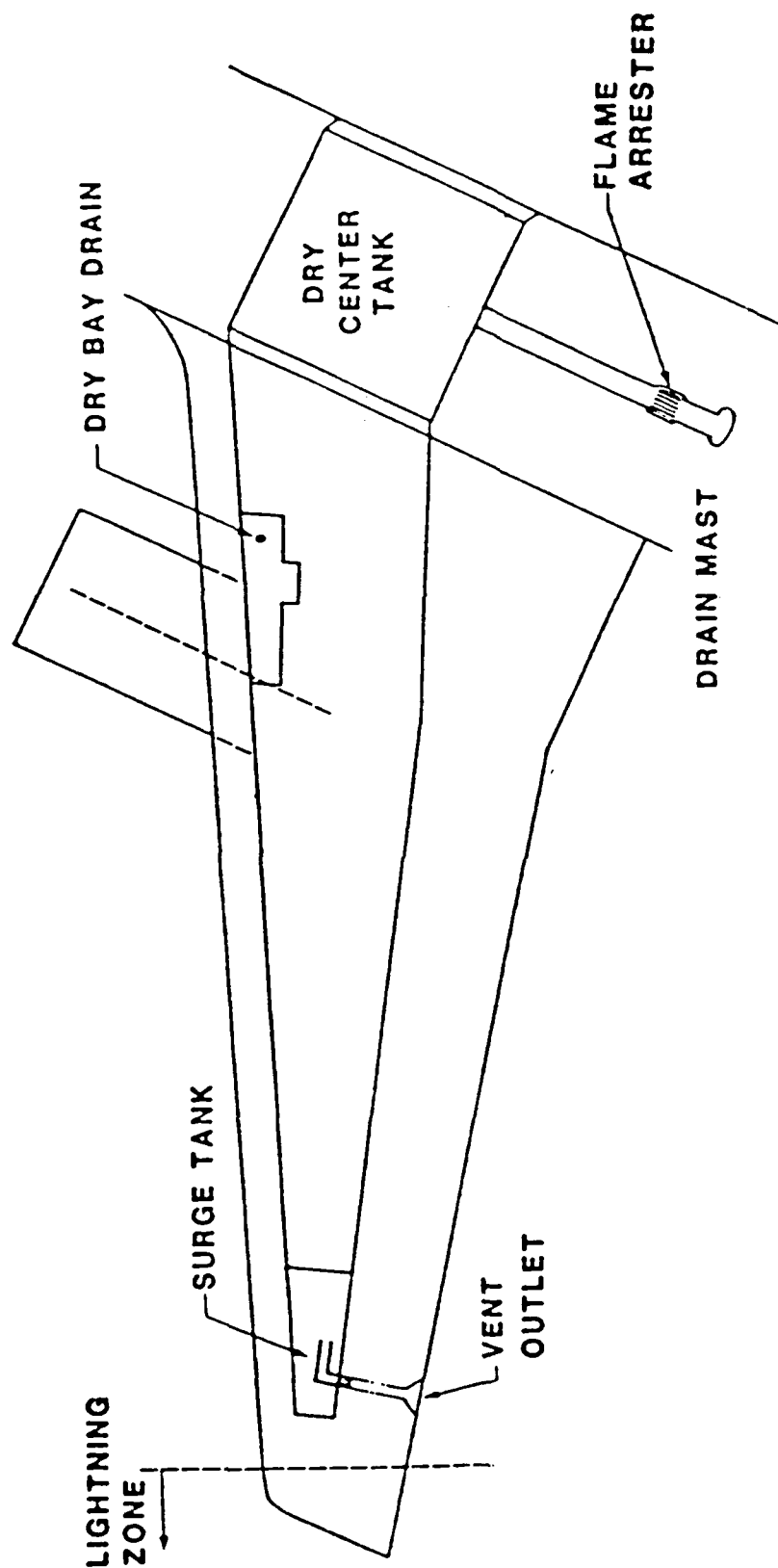
**ITEM**

- SHUTOFF VALVE IN PROTECTED AREA AT WING SPAR
- SPAR VALVE SHUTOFF BY FIRE HANDLE OR ENGINE CUTOFF
- DUAL SEPARATED WIRING

**OBJECTIVE**

- PROTECT FUEL SHUTOFF CAPABILITY DURING CRASH CONDITIONS
- SHUTOFF FUEL AT TANK EXIT UNDER EMERGENCY CONDITIONS
- PROVIDE BACKUP ELECTRICAL CIRCUIT TO SPAR VALVE

**FIG. 2 DRAINAGE PROVISIONS  
FLAMMABLE LEAKAGE AREAS**



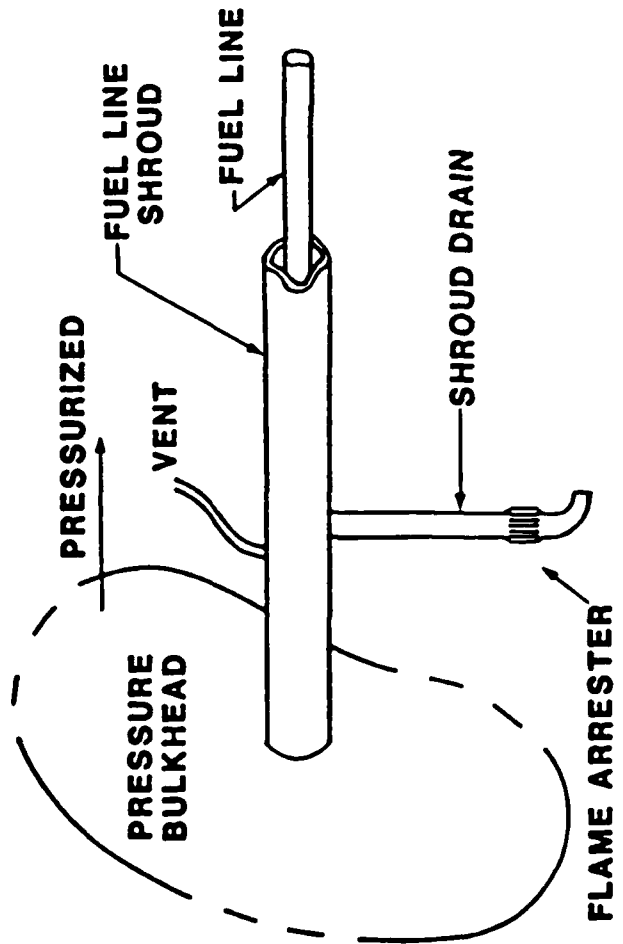
ITEM

OBJECTIVE

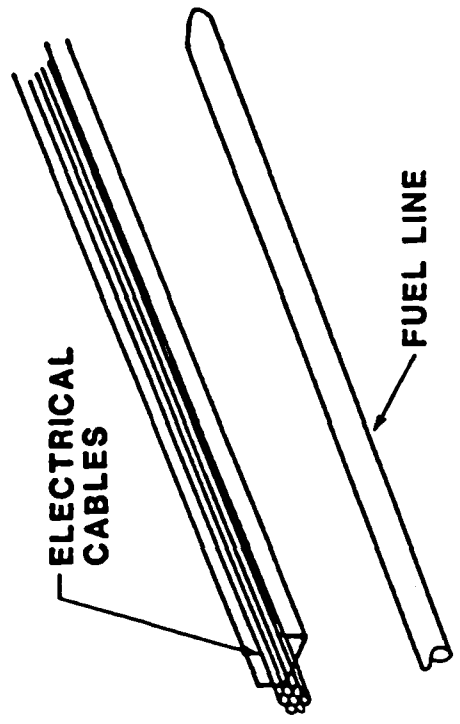
- |  |  |
|--|--|
| • VENT AND DRAIN OUTLETS OUT OF LIGHTNING HAZARD ZONES | • MINIMIZE LIGHTNING HAZARD  |
| • FLAME ARRESTERS IN ALL OVERBOARD VENTS AND DRAINS    | • MINIMIZE FLAME PASSAGE INTO FUEL TANKS FROM EXTERNAL FIRE SOURCE |

**Fig. 3**

**SHROUDED FUEL LINES IN PRESSURIZED COMPARTMENTS**



**FUEL LINES LOCATED BELOW AND SEPARATED FROM WIRING**



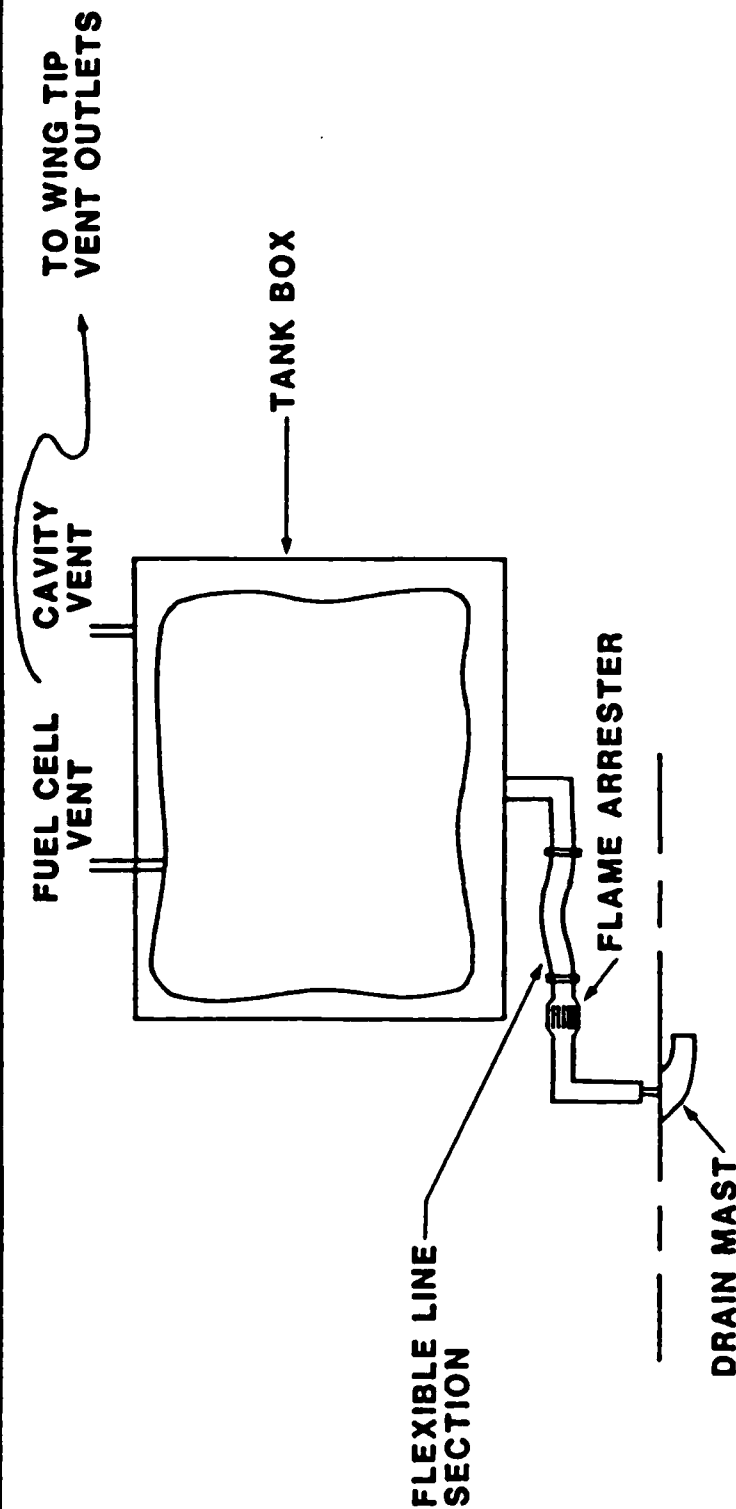
**ITEM**

- SHROUDED FUEL LINES (VENTED & DRAINED)
- SEPARATION OF FUEL LINES FROM WIRING

**OBJECTIVE**

- MINIMIZE POSSIBLE FUEL LEAKAGE IN PRESSURIZED COMPARTMENTS
- MINIMIZE EXPOSURE TO IGNITION SOURCE IN THE EVENT OF SYSTEM FAILURE

**FIG.4 AUXILIARY BODY FUEL TANK**



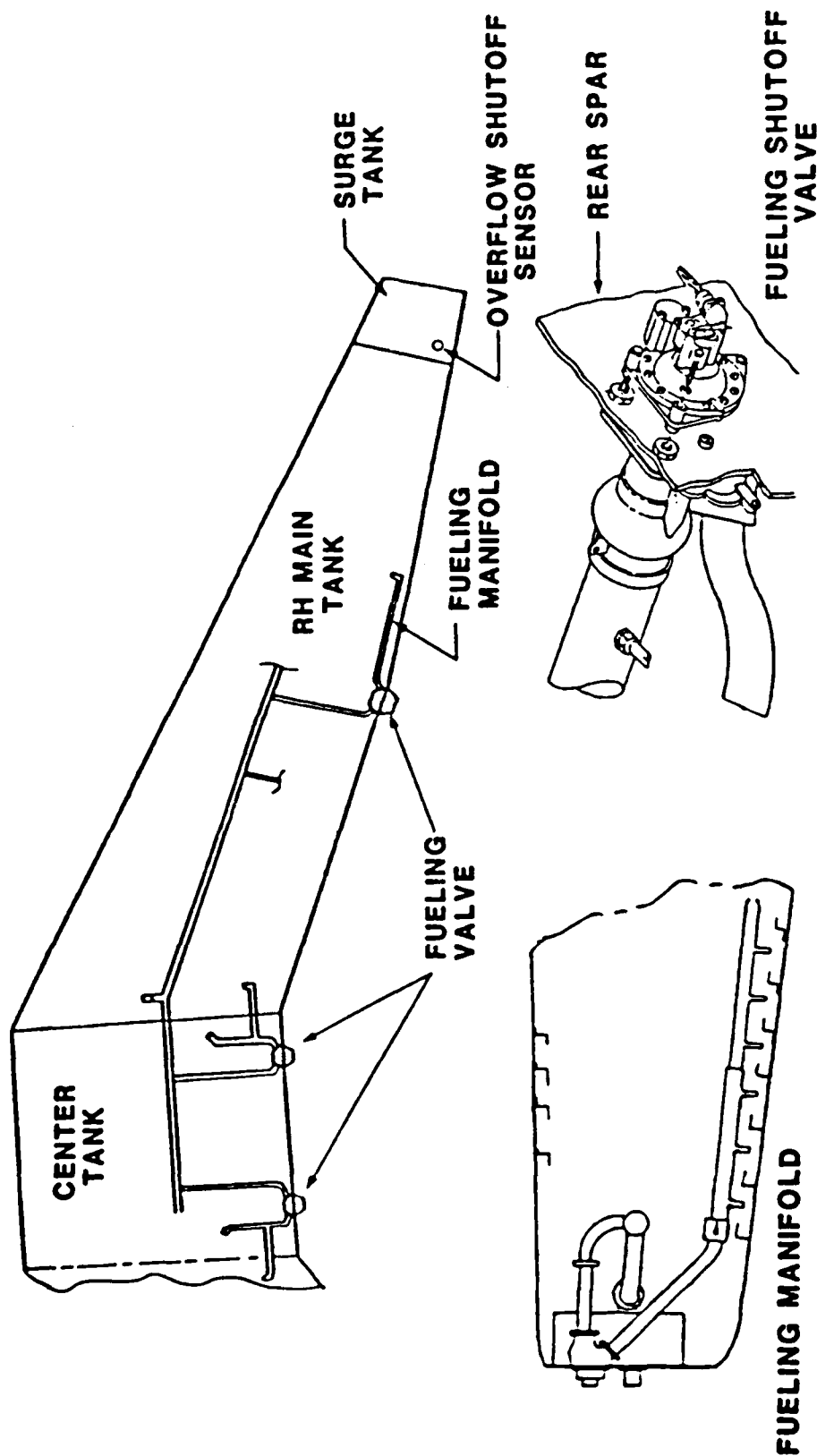
**ITEM**

- BODY FUEL TANK, FUEL LINES & FITTINGS LOCATED ABOVE MAJOR AIRPLANE LOAD STRUCTURES
- FLEXIBLE FUEL LINES (HOSES) INSTALLED IN AREAS VULNERABLE TO DAMAGE DURING A CRASH

**OBJECTIVE**

- DESIGN AND PLACEMENT TO MINIMIZE DAMAGE DURING CRASH CONDITIONS
- ALLOW A REASONABLE DEGREE OF DEFORMATION AND STRETCHING WITHOUT LEAKAGE

**FIG. 5 PRESSURE FUELING SYSTEM**

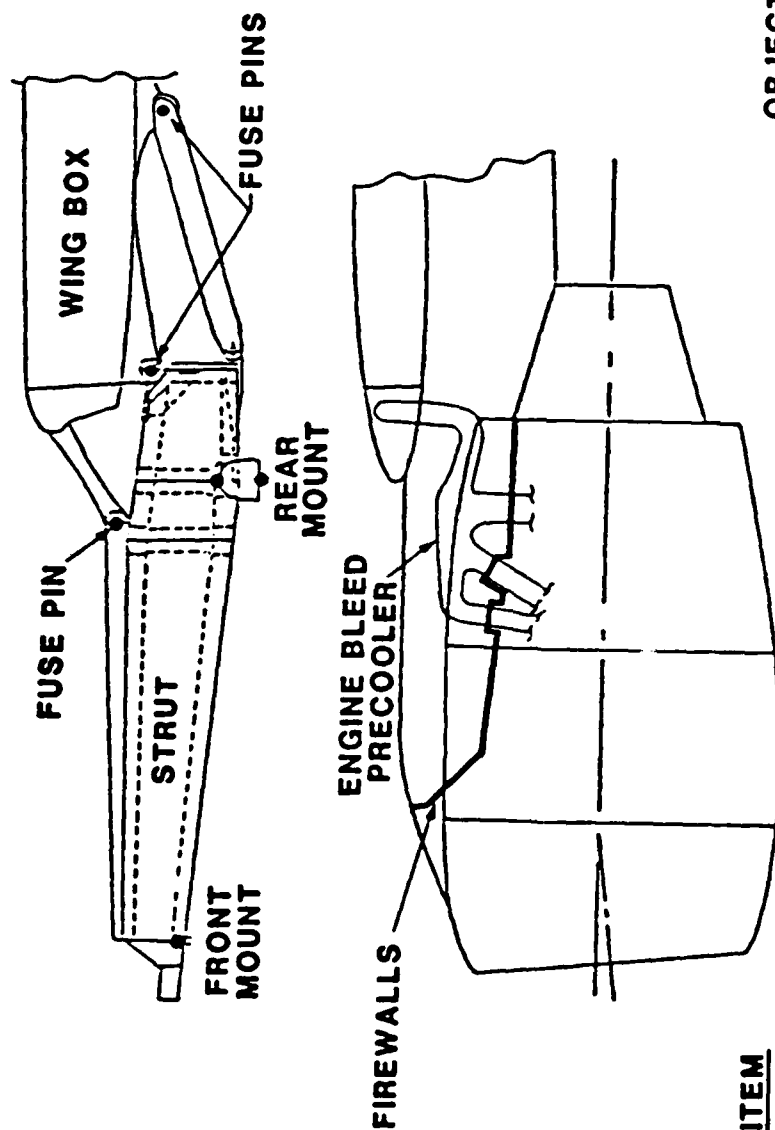


**ITEM**

**OBJECTIVE**

- AUTOMATIC PRESSURE FUELING SHUTOFF
- AVOID FUEL SPILLAGE DURING FUELING
- MULTI-ELEMENT TANK FUELING OUTLETS
- MINIMIZE STATIC CHARGE BUILDUP DURING FUELING OPERATIONS

**FIG. 6 INSTALLATION SAFETY FEATURES**



**ITEM**

- STRUT BREAKAWAY FEATURES (FITTINGS, LINES, WIRING)
- FIREWALLS
- BLEED DUCT TEMPERATURE
- NACELLE FUEL SYSTEM COMPONENT LOCATION

**OBJECTIVE**

- MINIMIZE AIRCRAFT DAMAGE DURING ENGINE SEPARATION
- MATERIAL SELECTION TO PROHIBIT FLAME PROPAGATION IN FLAMMABLE LEAKAGE AREAS
- DESIGN TO LIMIT BLEED DUCT TEMPERATURES AT WING FRONT SPAR
- LOCATE TO MINIMIZE FUEL SYSTEM LEAKAGE DURING WHEELS-UP LANDING

**FIG. 7 FUEL SYSTEM COMPONENTS**

---

- TANKS
- DISTRIBUTION SYSTEM
- VENT SYSTEM
- FUELING - DEFUELING SYSTEMS
- ENGINE & APU FEED SYSTEMS
- JETTISON SYSTEM
- FUEL QUANTITY MEASURING & INDICATING SYSTEM
- FLOW RATE MEASURING SYSTEM

## **FIG. 9 FUEL SYSTEM DESIGN GUIDELINES FOR MAXIMUM SAFETY**

---

- **FAIL-SAFE DESIGN**
- **MINIMIZE COMPONENTS BETWEEN TANK AND ENGINE**
- **MAXIMUM USE OF FUEL TANK FOR PLUMBING LINES,  
CONNECTORS & COMPONENTS**
- **LOCATE EXTERNAL TUBING & COMPONENTS ABOVE  
OR ADJACENT TO MAJOR AIRPLANE STRUCTURE**

SESSION IV: FUELS RESEARCH - PRIVATE/UNIVERSITY

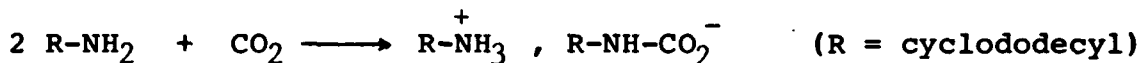
Chairperson: Dr. Martin Summerfield

## AMINE-CO<sub>2</sub> ADDUCTS AS AVIATION FUEL GELLING AGENTS

William W. Bannister  
Aviation Fuel Safety Company  
7 Livery Road, Chelmsford, MA 01824

### ABSTRACT

On addition of small amounts of cyclododecylamine (CDDN) to JP fuels, and with subsequent addition of CO<sub>2</sub> any time thereafter, a zwitterionic carbamate forms almost immediately to set up a gelling matrix within the fuel:



The system is proposed for application in impending controlled crash landings in which the crew would have a small amount of time (one or two seconds) to undertake measures to prevent fire developing from misting of fuel on impact. All fuel on board would be blended at the refinery with the CDDN agent; no blending of fuel with agent is required during fueling of aircraft. The dissolved agent does not separate; there are no changes in fuel characteristics until gelation is effected; the agent is compatible with water; and no in-flight degrading system is required. To effect gelation CO<sub>2</sub> tanks can be placed only at those fuel tanks posing greatest hazard to passengers in event of rupture, leaving ungelled fuel reserves for emergency flight operations. The gelled fuel has high impact stability, provides significant decreases in rate of vaporization, shows excellent reduction of flame and fireballing effects, will not gush from ruptured tanks, and may provide increased insulation from heat of combustion of burning fuel for aircraft exteriors. Use of liquid CO<sub>2</sub> also provides ancillary fire-blanketing effects, and would cool hot metal surfaces which would otherwise serve as ignition sources.

There is a possibility for use of the system in very low non-gelling concentrations which may still provide AMK characteristics, in which case there would be no weight penalties and no reaction time would be required. In preliminary experiments using a mixture of CDDN with AVGARD in JP-5, gelation time was greater but a pronounced increase in rheopectic (thickening) character of the fuel was also noted; thus, use of CDDN with other AMK agents may provide synergistic effects.

A feasibility exists for further optimization of the CDDN agent system which would permit gelation at even lower than the currently contemplated concentrations (2.2% CDDN).

Cost estimates, payload requirements, heat of combustion and NO<sub>x</sub> emission data, and a video tape of field tests will be presented.

## AMINE-CO<sub>2</sub> ADDUCTS AS JP FUEL GELLING AGENTS

(Copies of slides presented with this paper are provided at the end of this discussion.)

Conventional gelling agents previously considered for application for immobilization of aviation fuels in emergency situations suffer from very serious disadvantages (see Slide 2). Thus, it is extremely difficult to blend such agents into fuels due to gelatinous interfaces which form between gelant and the fuel solvent. This would necessitate very considerable expenditures of energy with massive blending equipment and much time, with non-homogeneous gelled mixtures resulting. A very serious problem would also exist in the event of inadvertent activation of the gelation system while in normal flight operations, resulting in complete immobilization of all the fuel for the aircraft with obvious disastrous consequences.

Our group had developed a novel gelation system for use in oil spills at sea, which entirely circumvents these disadvantages of conventional gelling agents. Thus, small amounts of cheap, non-toxic cyclododecylamine (CDDN; see slides 3 and 4) can be dissolved easily and very quickly into the oil. This solution remains completely fluid until carbon dioxide is added in small amounts. A reaction takes place instantly to form a carbamate with complete gelation of the oil occurring practically immediately. (See slide 4 for a summary of this reaction.)

It occurred to us that this system would be of possible application in terms of immobilizing aircraft fuel when, and only when gelation would be required. After discussions with FAA

representatives, we set up requirements for a prototype aircraft fuel gelation system, with the understanding that further improvements may be necessitated if these initial requirements could be met. Thus, the agent system would have to provide excellent anti-misting characteristics, rapidly (within a very few seconds after onset of emergency conditions). There should be a capability for providing sufficient ungelled fuel reserves to be available for emergency operations. The agent should be cheap and non-toxic, and provide good fuel compatibility. No distribution or blending equipment should be required, either on board the aircraft or on the ground. (See slide 5.)

In our initial efforts along these lines, in 1983, our system required 7% amine concentrations. As research continued, with development of improved accelerators this requirement was successively lowered to 4%, then to 3%, and then to 2%. This research is ongoing and it appears that insofar as gelation is concerned, this may be achievable at concentrations down to 1%. Moreover, we have recently been investigating what is occurring at concentrations much lower than the existing formulation of 2% CDDN and 0.2% glycol ether accelerator (see slide 6). We believe that a distinct capability may exist for adequate anti-misting character to be achievable, even though the fuel is not gelled, at concentrations less than 1%. Ramifications of this latter concept will be discussed in detail later in this paper.

A very important aspect of the overall formulation of the CDDN system is that water is not harmful to the gelling activity; as a matter of fact, water is beneficial and can be present in any

amount, from traces quantities to gross contamination.

In terms of use of this agent system for gelation effects, our group envisions that this would be invoked only in controlled crash landing situations in which the aircraft crew would have as much as two seconds for implementing counteractive measures to reduce fire hazards; the system thus would not be applicable for mid-air collisions or similar catastrophic events of instantaneous proportions in which there would be virtually no possibility for survival by passengers or crew, anyway. (See slide 7.)

In terms of possible use of this agent system as an anti-misting agent, with very low (perhaps a few tenths of one per cent) concentrations below capability for complete gelation but with anti-misting effects displayed by conventional AMK agents now being considered, the scenario changes considerably. Now, the the agent would be both blended with the fuel and also carbonated at the refinery. Thus, the crew would not have to activate the system, there would be no reaction time involved, and the agent would be an effective countermeasure for all crash scenarios.

(The CDDN agent does not separate from the blended fuel. Unlike aromatic amines, cycloaliphatic amines such as CDDN do not oxidize or otherwise decompose on standing, and there would be a storage life of years for the blended fuel. Very importantly, there would be no requirement for massive blending equipment and lengthy blending time prior to fueling of the aircraft.)

Our group did not have any means of testing AMK effects of

the gelled fuel. Accordingly we developed a testing scheme which, we believe, provides some indication of the capability of CDDN to reduce fireballing and other flame hazards. Three mortars were constructed, each being a 16" length of steel pipe with inside diameter of 1.25" and wall thickness of 0.25", with a threaded cap for enclosing one end. A hole of 0.125" diameter was drilled in the each cap to accomodate an electrically activated model rocket igniter implanted in a plastic lid of 1" diameter and 0.5" depth, containing 8 grams of black powder. The lid was secured to the inside base of the cap with epoxy glue and a paper cover placed over the black powder charge with more epoxy applied to coat the paper cover and to seal the firing hole in the base of the cap. Firing of each mortar round was conducted over a lake at an inactive quarry. In the first mortar was placed 60 ml of water to provide an indication of spray pattern and trajectory of liquid charges. The second mortar was loaded with 75 ml of ungelled JP-5 with 2.2% CDDN agent but with no carbonation to gel the fuel. In this shot a large fireball was formed by ignition of the misted fuel. In the third mortar was placed 100 ml of JP-5 containing 2.2% CDDN agent which was then carbonated with immediate gelation. Upon firing of this round, the gelled fuel shot out as a waxy wad more than 100 feet over the lake; there was virtually no fireball formation. The observations made from this test were:

1. Gelled fuel holds up excellently under violent mechanical stress -- practically all the fuel was observed to be floating on the lake as intact gel.
2. There was a very dramatic reduction in fire -- both

in terms of amount of fuel burnt, and in fireballing effects (again, there was no fireball formation).

(A video tape presentation of these quarry tests is included in this presentation; see page 9 of the slide enclosures.)

Our group would like to suggest that this type of test could perhaps be useful for general small scale testing of fire-reducing effects of AMK agent candidates.

Slide 10 in this presentation illustrates the concept we propose for utilization of the CDDN agent system. In the gelling mode, fuel which has been pre-blended with the requisite amount of CDDN agent is loaded into the aircraft's fuel tanks and burnt in the engines as a liquid fuel with all the characteristics (i.e., no change in viscosity, vapor pressure, flammability, or other properties from very low to ambient high temperatures) of conventional JP fuels. Thus, no need exists for polymer degrading or or heavy duty filtering and pumping equipment to accomodate the fuel over and above that needed for ordinary JP fuels. Liquid CO<sub>2</sub> tanks would be placed only at those fuel tanks in which gelation would be desired, to be activated by trigger switch by the pilot in the event of emergency. Thus, provision would exist for total inability to gel those tanks selected for reserves for emergency flight operations, by simply not having CO<sub>2</sub> available at these tanks. (CO<sub>2</sub> tanks could be located to service all fuel tanks, if desired, with a separate switch to activate reserve tanks when it became apparent that a crash was inavoidably imminent.)

If it can be established that AMK character exists in fuels

containing less than a gelling concentration of CDDN (e.g., perhaps at 0.2% rather than 2%), then the CDDN and CO<sub>2</sub> could both be blended into the fuel at the refinery. In this mode, there is no need for CO<sub>2</sub> tanks on board the aircraft, nor for activating controls: the agent system now is of the same description as pertains to conventional AMK agents (without any need for blending, degrading, or heavy duty filtering and pumping equipment on board the aircraft, however).

(We believe that changes in rheology of the fuel should be anticipated between the extremes of 0% content of CDDN agent and 2.2% carbonated CDDN in the completely gelled fuel formulation, and this is a possibility we are suggesting for future study.)

In terms of heat of combustion considerations, as is indicated in Slide 11, there is actually a small increase in the available heat of combustion which would arise from incorporation of 2.2% CDDN agent into the fuel.

Payload reductions (i.e., the weight of the entire CDDN system) are presented for a 747 aircraft in slide 12, these totalling 6,100 pounds, assuming that the fuel is to be gelled by carbonation of 2.2% CDDN agent. (For smaller aircraft weight requirements would be correspondingly smaller.) If the non-gelling mode which might be available from use of a very small percentage of carbonated CDDN were to be feasible, the weight requirements essentially drop to zero; no CO<sub>2</sub> equipment would be required at all.

Preliminary cost calculations are presented in Slide 13. As can be noted here, these considerations do not include the loss of perhaps twenty passenger seats due to payload losses of about 6000 pounds incurred by installation of the CO<sub>2</sub> equipment. This cost analysis assumes use of a 2.2% CDDN formulation, in which case the agent cost alone would amount to a little less than 25 cents per gallon of fuel, which of itself would be prohibitively high. However, these costs are based on projected pilot plant costs for the amine agent, and if full scale production (in terms of millions rather than thousands of gallons per year) were to be realised, the cost would be very considerably reduced -- probably to less than half the small scale pilot production cost. Another reduction of the order of up to 50% could be achieved if agent concentration requirements could be reduced from 2.2% to 1% or so, as would seem feasible with our ongoing research involving optimization of the gelling agent formulation.

Moreover, if the agent can be used in very low concentrations (perhaps 0.2% or so), below gelling strength but still providing AMK characteristics, the cost would then be projected to just a few cents per gallon, and with no requirement for loss of passenger seats since there would be no onboard CO<sub>2</sub> requirements.

Thus, there are fairly good possibilities for very large reductions (by as much as 90%) in these preliminary high cost calculations for use of this agent system.

Slide 14 provides calculations regarding projected nitrogen oxide emissions arising from combustion of the CDDN amine entity,

based on a 2.2% agent formulation. As is noted, this would result in about 0.09% of NO in the combustion gases; on the other hand, combustion of atmospheric nitrogen in jet engines produces as much as 3% NO, or 33 times as much as would be accounted for from that produced by the introduction of this amine additive. Reduction of the amine concentration by optimization of agent formulation, or by use of the amine as a non-gelling AMK agent would further reduce this already small NO emission source. Thus, it would not appear that significant engine corrosion or atmospheric pollution problems would be anticipated from this standpoint.

As is noted in Slide 15, there appears to be a possibility for compatibility of the CDDN agent with other AMK agent systems. In preliminary experiments performed at the FAA Technical Center at Atlantic City using a mixture of CDDN with AVGARD in JP-5, gelation time was considerably longer but there was also an immediate and pronounced increase in rheotropic character (i.e., thickening upon agitation) of the fuel, beyond that afforded by AVGARD alone. Thus, use of CDDN with AVGARD appears to offer synergistic possibilities in terms of anti-misting performance, along with a definite feasibility for further optimizing the CDDN agent formulation to provide both rapid gelation and increased rheotropic character for JP fuels in emergency controlled crash landing situations.

There are three factors required for flame generation and propagation, as is noted in Slide 16: fuel, oxygen, and a source of heat. Denial of any one of these requirements is all that is required for prevention or extinguishing of any fire. As proposed

for implementation in emergency controlled crash landing situations, the CDDN agent system should serve to reduce fire hazards from all three standpoints. Thus, as was observed in the mortar tests previously discussed in this presentation, gelling of the fuel appears to provide very good suppression of fire by immobilizing the liquid fuel and preventing its misting. By using the  $\text{CO}_2$  in the gelling reaction, an excellent inerting atmosphere would also be provided, as is the case in any  $\text{CO}_2$  fire extinguishing system. Finally, the sparging of liquid  $\text{CO}_2$  is accompanied first by flashing of the liquid into cold Dry Ice, which would be expected to provide an important cooling effect, particularly with regard to hot metal surfaces which are apparently important sources of ignition in aircraft fire situations. (Along these same lines, the elimination of the fireballing effect as is provided by the immobilization of the fuel by gelation would also be expected to significantly reduce the heating effect.)

(For a summary of the overall characteristics of the proposed CDDN system, see remarks in the Abstracts at the beginning of this paper, and also summary remarks contained in Slides 18 and 19 in the attached enclosure.)

COPIES OF SLIDES PRESENTED IN PAPER ON  
AMINE-CO<sub>2</sub> ADDUCTS AS JP FUEL GELLING AGENTS

-1-

AMINE-CO<sub>2</sub> ADDUCTS AS JP FUEL GELLING AGENTS

William W. Bannister  
William A. Curby  
John R. Pennace  
Admiral Owen W. Siler, USCG (Ret.)

AFSC

-2-

DISADVANTAGES OF PREVIOUSLY CONSIDERED  
GELLING AGENTS FOR USE WITH JP FUELS

Mechanical blending difficulties

Excessive gelation time

Non-homogeneity of gel

Loss of fuel reserves after gelation

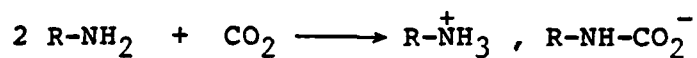
Possibilities for accidental gelation of  
entire fuel reserves due to human error

Weight penalties resulting from installation  
of massive distribution and blending systems

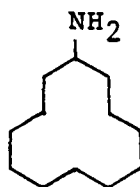
-3-

CYCLODODECYLAMINE (CDDN) AS A GELLING AGENT  
IN JP FUEL FORMULATIONS

Amine Carbamate Formation



e.g.,  $\text{R-NH}_2$  = cyclodecylamine (CDDN)



REQUIREMENTS

- Excellent anti-misting characteristics
- Fast gelation time (less than 10 seconds)
- Availability of fuel reserves after gelation
- Economy
- Low toxicity
- No massive distribution equipment
- No in-flight blending requirements;  
capability for blending at refinery
- Compatibility in terms of fuel combustion

JP/GELLING AGENT FORMULATION

(For blending at refinery or at airport  
terminal fuel storage facilities)

2.0% CDDN

0.2% DOWANOL PPh GLYCOL ETHER

(Trace) Water

97.8% JP FUEL

CDDN SYSTEM USAGE SCENARIO

Controlled crash landings

Two seconds or more reaction time for  
crew

NOT generally applicable for mid-air  
collisions or other catastrophic  
events of instantaneous proportions

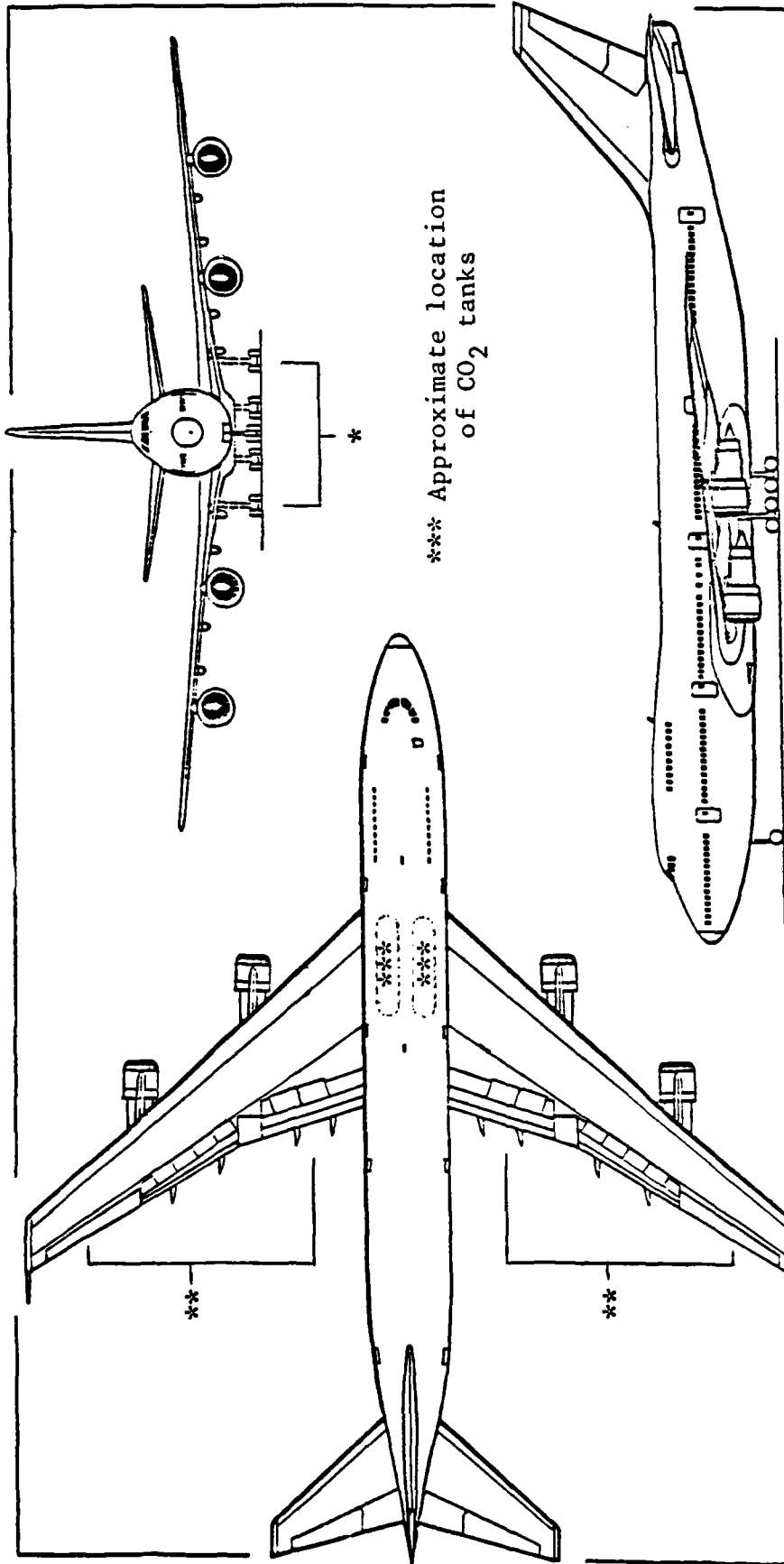
FUEL DETONATION TESTS

MERRILL QUARRY

NORTH CHELMSFORD, MASSACHUSETTS

16 OCTOBER 1985

(Video tape presentation of results of detonation tests at Merrill Quarry. Points of interest to be emphasized are the fireballing effects displayed when 75 ml of ungelled JP fuel is shot from a mortar using a black powder charge, and the complete lack of fireballing under identical conditions with 100 ml of JP fuel gelled with 2.2% CDDN agent. In the latter instance most of the gelled fuel was propelled, without burning, over 100 feet as a gelled wad.)



\*\*\* Approximate location  
of CO<sub>2</sub> tanks

**Boeing 747-200B four-turboprop heavy transport aircraft (*Pilot Press*)**

JANES AIRCRAFT  
(1980)

	Center Wing Tank	17,160 gallons		
*	Two Inboard Main Tanks	25,100 gallons		
	Two Inboard Reserve Tanks	1,068 gallons		
**	Two Outboard Main Tanks	8,970 gallons		
			TOTAL GELABLE CAPACITY:	
				43,328 gallons
			(CANNOT BE GELLED; AVAILABLE FOR EMERGENCY OPERATIONS)	

AD-A169 784

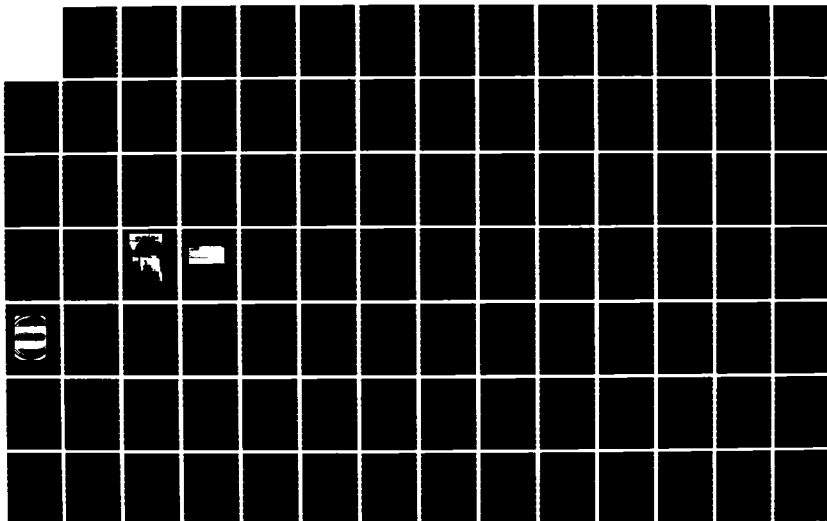
PROCEEDINGS OF FUEL SAFETY WORKSHOP HELD AT ALEXANDRIA  
VIRGINIA ON 29 OCT. (U) FEDERAL AVIATION ADMINISTRATION  
WASHINGTON DC PROGRAM ENGINEE. 31 DEC 85  
DOT/FAR/PH-86/13

4/4

UNCLASSIFIED

F/G 21/4

NL





# HEAT OF COMBUSTION CONSIDERATIONS

Assume 52,300 gallons (198,000 liters) fuel:

2.2% CDDN (4,356 liters)  
97.8% JP (193,644 liters)

$$\Delta H_{\text{comb,JP}} = 8,590 \text{ kcal/liter}$$

$$\Delta H_{\text{comb,CDDN}} = 10,080 \text{ kcal/liter}$$

For unformulated JP fuel:

$$(198,000 \text{ liters})(8,590 \text{ kcal/liter}) =$$

$$17.00 \times 10^8 \text{ kcal from on-board fuel}$$

For 2.2%CDDN/97.8%JP fuel formulation:

$$(4356)(10,080) \text{ kcal} + (193,644)(8,590) \text{ kcal}$$

$$= 17.07 \times 10^8 \text{ kcal from on-board fuel}$$

(an increase of 0.4% in available heat  
of combustion)

PAYLOAD REDUCTIONS INVOLVED WITH CDDN SYSTEM

Weight differential, displacement of 1050 gallons JP by CDDN	2,600 lb
2 CO <sub>2</sub> tanks, each with full load of 750 lb of liquid CO <sub>2</sub>	3,000 lb
CO manifolds, regulators and valves	500 lb

---

TOTAL CDDN SYSTEM WEIGHT REQUIREMENT 6,100 lb

Note: No pumping, filtering, cracking or  
in-flight blending equipment  
required for the CDDN system.

COST CONSIDERATIONS

(Exclusive of payload losses due to  
installation of CDDN agent system)

Assume 80% combustion of 53,200 gallons of  
aircraft fuel in a typical extended flight  
operation (i.e., 42,560 gallons expended).  
Assume 2.2% CDDN agent formulation (i.e., 940  
gallons CDDN agent expended); at \$12.50 per  
gallon, agent cost is \$11,750.

At \$1/gallon for the JP displaced by the CDDN  
agent, this offset reduces the agent cost to  
\$10,810, for an increase in fuel price of  
about 25 cents per gallon.

NITROGEN OXIDE FORMATION

Assume 100 g of 2% CDDN/98% JP formulation:

98 g  $-(CH_2)_n$  = 7.00 mole  $-CH_2-$

2 g CDDN = 0.01 mole  $-CH_2-$  + 0.01 mole N  
[O]

7.01 mole  $-CH_2-$   $\xrightarrow{[O]}$  7.01 mole (CO<sub>2</sub> + H<sub>2</sub>O)  
= 435.3 g CO<sub>2</sub> + H<sub>2</sub>O

0.01 mole N  $\xrightarrow{[O]}$  0.01 mole NO = 0.4 g NO

(NO represents 0.09 % of total emission from  
burning 2 % CDDN. By comparison, oxidation  
of nitrogen in air while burning ordinary JP  
produces 3 % NO, or 33 times this quantity.)

COMPATIBILITY OF CDDN SYSTEM  
WITH CONVENTIONAL AMK AGENTS

On mixture of 2.2% CDDN agent with JP/AVGARD:

considerably longer gelation time

pronounced increase in rheopectic  
character after addition of CO<sub>2</sub>

Ramifications:

synergistic effects in use of CDDN  
with other AMK agents

possibilities for further optimizing  
of CDDN agent for faster gelation  
when used with other AMK agents

REDUCTIONS OF FIRE HAZARDS BY CDDN

CO<sub>2</sub> blankets  
fuel tanks



Massive cooling  
of metal surfaces  
by Dry Ice effect

Gelation of fuel  
prevents misting,  
reduces fireballing

GENERAL ADVANTAGES OF  
CDDN SYSTEM

NO CHANGES IN FUEL CHARACTERISTICS IN COMPARISONS  
WITH CONVENTIONAL JP FUELS, FROM VERY COLD TO HOT  
TEMPERATURES

Same vapor pressure

Same viscosity

Essentially same heat of combustion  
(slight increase noted)

Essentially same NO emissions  
(slight increase noted)

Same heat transfer coefficients

OVERALL COMPATIBILITY WITH WATER

BROAD SPECTRUM OF FUEL COMPATIBILITIES (JP-4,  
JP-5, GASOLINE, ETC.)

FUEL AND GELLING AGENT CAN BE BLENDED AT REFINERY;  
NO NEED FOR BLENDING JUST PRIOR TO FUELING

INDEFINITE STORAGE TIME; STABLE FOR YEARS

NO IN-FLIGHT BLENDING OR DEGRADING (POLYMER  
CRACKING) SYSTEMS REQUIRED

No massive equipment weight and volume  
displacements

No heavy duty pumps required for pumping  
viscous fluids

No separation of fuel components

No special filtering equipment

No energy expenditures for operation of  
above equipment

CAPABILITY FOR SEALING OF LEAKING TANKS BY  
EXTERNAL APPLICATION OF SMALL AMOUNTS OF CO<sub>2</sub>

GENERAL ADVANTAGES OF CDDN SYSTEM (CONTINUED)

AFTER APPLICATION OF CO<sub>2</sub>:

HIGH VELOCITY IMPACT STABILITY -- NO MECHANICAL DEGRADING

POSSIBILITY FOR INCREASED INSULATING EFFECTS FROM HEAT OF BURNING FUEL, BY THICK GEL ON EXTERIOR AIRCRAFT SURFACES

SIGNIFICANT DECREASE IN RATE OF VAPORIZATION FROM GELLED FUEL

EXCELLENT REDUCTION OF FIREBALLING AND OTHER FLAME EFFECTS IN SMALL SCALE TESTS

INERTING ATMOSPHERE AND COOLING OF HOT METAL SURFACES BY ACTION OF LIQUID CO<sub>2</sub>

ONLY ONE EXTRA CONTROL NEEDED FOR ACTIVATION OF GELATION, BY AIRCRAFT CREW

PROVISION FOR UNGELLED EMERGENCY FUEL RESERVES FOR EXTENDED EMERGENCY FLIGHT OPERATIONS

GELLED FUEL WILL NOT GUSH FROM RUPTURED FUEL TANKS

NOT PERMANENTLY IRREVERSIBLE: GELLED FUEL CAN READILY BE FLUSHED FROM AIRCRAFT FUEL TANKS USING MODERATELY HIGH PRESSURE WATER HOSES

POSSIBLE SYNERGISTIC EFFECTS OF CDDN AGENT SYSTEM ON ADMIXTURE WITH OTHER AMK AGENTS

POSSIBLE CAPABILITY FOR USE OF CDDN/CO<sub>2</sub> ADDUCT IN VERY LOW CONCENTRATIONS AS NON-GELLED AMK AGENT:

In this mode:

No requirement for on-board CO<sub>2</sub> tanks

Fuel can be blended at refinery with CDDN and CO<sub>2</sub>

No extra controls needed for activation by aircraft crew

Agent is available for use at all times as AMK agent -- no reaction time required

POSSIBLE CAPABILITY FOR MORTAR TEST FOR USE IN MEASURING REDUCTION OF FIRE-BALLING AND OTHER FLAME EFFECTS OF AMK CANDIDATES

## CRASH SAFETY FUEL TANK

Mr. H. Allen Tansill  
Consultant  
Santa Barbara, California

I have a video presentation, but I would like to preface it with a few remarks. I am a lone inventor, not associated with any engineering, chemical, or financial research support, so my presentation does not have the polish of some of these other presentations. I should explain before the video that all we are showing is a small cross section of this device that I propose and the best way to illustrate is the stomach. The stomach has the intestines, and one end of the stomach is connected to the intestines, and the other end of the intestines, we know where that goes. It is the same in my fuel tank. One end of the tank is connected to the small device, and the other end of the tank is connected to the engines. I'm only showing a cross section of the tank. Just as intestines can have a considerable length, a fuel tank could be a box, like a wing section, or it could be a coffin shape, or it could be an elongated shape similar to intestines. There is a wave of peristaltic motion, and the best way I can illustrate that is as kids we pass a baseball bat, and you grab it here, and here, and here. If you squeeze an elastic material in this fashion you will squeeze out any fluid inherent in it. Though the drawings show considerable thickness, realize that you could take a large body of water, put a few molecules of film and greatly slow down the evaporation. This has been used in desert regions.

Now let's roll the video.

My name is Horace Allen Tansill. My family and I narrowly escaped tragedy in a fire in our residence when I was five years of age. After being a private pilot over 50 years, that experience when I was five years of age motivated me to come up with this concept of fuel safety mangement. The object of this concept is to save lives, because when an airplane crashes, and there is vaporization of the fuel, followed by a crash fire, many lives are needlessly lost. If we can lengthen the time to give people sufficient time to evacuate the plane, many lives will be saved. In aircraft crash situations where large structures are crushed and torn into many pieces, and distorted in every imaginable manner, it is important to look toward the intermolecular forces of absorption, adsorption, capillary action, and surface tension to reach stable conditions. This concept is to use a series of capillaries to contain the aviation fuel. These capillaries are configured in a hexagonal manner, much as the bee comb, to pack the maximum aviation fuel in the minimum space. There is a space set in the center of the capillaries whereby the engine exhaust, carbon dioxide, and fire extinguishing materials may be applied to squeeze the aviation fuel from the capillaries to supply the engines. I think we can illustrate the series of capillaries best by this drawing.

If you will notice the red and the little honeycomb, they represent the various capillaries, red representing the aviation fuel and the honeycomb representing the capillaries containing the fuel. This drawing is greatly magnified for purposes of simplification. These vertical lines represent a very flexible squeeze bladder, to the inside of which we can apply aviation

engine exhaust which has already been combusted and is relatively inflammable, or we can apply carbon dioxide, the fire extinguishing foam or the fire extinguishers. Upon the application of pressure to these interior bladders, we cause it to expand, therefore squeezing the capillaries, causing them to squeeze out the aviation fluid to supply the engine. Eventually we reach the state where the total structure is full of carbon dioxide, fire extinguisher, or engine exhaust, all the fuel having been squeezed out of the capillaries. The converse is used for filling the tank. We begin with the empty tank, we release the pressure in the squeeze bladder, gradually bringing it back to its flat configuration, while at the same time filling the fuel from the fuel tank, thereby withdrawing exactly two cubic centimeters of 100 octane aviation fuel. I am spreading that into a pyrex dish. You will observe that I am approaching it with a flame, and the flame does not need to touch the fuel because the vapors cause the ignition. We all know the results of such things in crash situations as far as the loss of human life. You'll note I am withdrawing two centimeters of the same high octane fuel into this capillary tube. Now I am going to bring the lighted flame toward the fuel end of the capillary. Notice the fuel moving away from the flame as the capillary shrinks. This is made of a heat-shrink capillary material. Now, this tube contains the aviation fuel, and if you look you can see the fuel balling and separating as I separate the plastic tube. I am putting the end in the flame to show that it does not ignite. Now I am cutting the tubing into pieces, which I am piling up. Notice the fuel separating as the heat of the flame touches it. You will note that there are no explosive vapors to ignite as long as the fuel is contained capillaries. I am now passing the flame over a fuel-containing capillary to show the safety inherent by the thin film of plastic between the fuel and flame. Contrast this to fuel that is not contained in any safe structure.

Any method used must be very light in weight, so as not to reduce the aircraft payload. Secondly, it must occupy a minimum volume leaving the maximum space for the tanks to carry their fuel. In addition any useful system must safely contain the maximum amount of fuel in a crash situation. Even though the aircraft fuel tanks are pierced, torn, distorted or broken into pieces, and these pieces may be in contact with redhot metals, the fuel will not ignite.

## FAA PRESENTATION

### GTA/BASF ANTIMISTING FUEL RESEARCH

by Jerry C. Trippe

I PRESENTED A PAPER AT THE 1981 ANTIMISTING FUEL CONFERENCE AT ATLANTIC CITY AND PERHAPS THAT IS THE REASON I WAS ASKED TO SPEAK TODAY. AT THAT TIME, I DESCRIBED THE RESULTS OF A SMALL PROGRAM MY COMPANY, GENERAL TECHNOLOGY APPLICATIONS, INC., HAD PERFORMED FOR THE FAA, INVESTIGATING THE APPLICATION OF A PROPRIETARY DISSOLVING PROCESS TO ANTIMISTING FUELS. IN THAT PAPER, I SUGGESTED THAT ONE OF THE ADDITIVES WE WORKED WITH, POLYISOBUTYLENE (PIB), HAD QUALITIES WHICH MADE IT A SUPERIOR ANTIMISTING ADDITIVE. I AM BACK WITH THE SAME MESSAGE, BUT THIS TIME WITH TEST RESULTS WHICH SUPPORT THE EARLIER CONCLUSION, AND A PARTNER, BASF, THE GERMAN CHEMICAL COMPANY, WHICH HAS AGREED TO A JOINT PROGRAM TO EXPLOIT THE POTENTIAL OF PIB FOR INCREASING AIRLINE PASSENGER SAFETY.

THE GTA/BASF PROGRAM DIVERGES SIGNIFICANTLY FROM THE DIRECTION OF THE FAA'S EFFORTS OVER THE PAST 10 YEARS. FIRST, WE HAVE ASSUMED THAT AN EFFECTIVE ANTIMISTING FUEL HAS TO WITHSTAND MUCH GREATER FORCES THAN THOSE FROM WIND SHEAR AT AIRCRAFT LANDING SPEEDS. WE BELIEVE THAT THE MANCHESTER INCIDENT AND THE FAA TEST LAST DECEMBER IN THE CALIFORNIA DESERT MAKE THIS CLEAR, WHETHER THE SHEAR IS DUE TO THE PENETRATION OF A FUEL TANK BY HOT ENGINE PARTS OR THE EXHAUST OF A JET ENGINE.. SECOND, THE FAA HAS BASED ITS JUDGEMENT OF A

SUCCESSFUL ANTIMISTING FUEL ON WHETHER OR NOT IT SUPPRESSES A SIZEABLE GROUND FIRE IN THEIR WING SPILLAGE TESTS. THE MEASURE OF MERIT OF AN ANTIMISTING FUEL SHOULD RELATE MORE DIRECTLY TO HOW AN ANTIMISTING FUEL CAN BENEFIT PASSENGER SAFETY. WE SEE THAT PASSENGER SAFETY CAN BE IMPROVED BY ELIMINATING SUDDEN CATASTROPHIC FUEL EXPLOSIONS AND WE BELIEVE ANTIMISTING FUEL CAN ACHIEVE THIS GOAL WITHOUT REQUIRING MODIFICATION OF AIRCRAFT SYSTEMS AND AT A COST OF LESS THAN ONE CENT PER GALLON. THIS IS A LOGICAL EXTENSION OF JET-A WHICH INCREASED SAFETY BY REDUCING THE VAPOR IGNITION HAZARD.

FIRST, I WILL GO QUICKLY OVER GTA AND BASF WORK IN ANTIMISTING RESEARCH, AND THEN GO MORE SPECIFICALLY INTO WHAT WE HAVE OBSERVED AND OUR CONCLUSIONS BASED ON THOSE OBSERVATIONS.

GTA ENTERED ANTIMISTING FUEL RESEARCH IN AN ATTEMPT TO FIND MARKETS FOR ITS PROPRIETARY DISSOLVING PROCESS FOR HIGH MOLECULAR WEIGHT POLYMERS. UNDER CONTRACT TO THE FAA IN LATE 1980 AND EARLY 1981, GTA DEMONSTRATED THE USE OF ITS PROCESS FOR IN-LINE DISSOLVING OF TWO POLYMERS WITH KNOWN ANTIMISTING BEHAVIOR; ICI'S FM-9, THE FAA'S CANDIDATE FOR AN ANTIMISTING FUEL, AND BASF'S OPPANOL B-230, A HIGH MOLECULAR WEIGHT POLYISOBUTYLENE (PIB). THE RESULTS OF THIS PROGRAM WERE REPORTED AT THE 1981 ANTIMISTING FUEL SYMPOSIUM.(1) ONE RESULT WAS THE DISCOVERY THAT IN COMPARATIVE FAA TESTS, OPPANOL B-230 WAS SUPERIOR TO FM-9 IN MIST FIRE SUPPRESSION. IN MAY 1981, WE RESPONDED TO THE FAA'S RFP FOR ALTERNATIVE ANTIMISTING FUEL ADDITIVES WITH A PROPOSAL TO EVALUATE A NEW, HIGHER MOLECULAR WEIGHT

PIB. OUR THESIS WAS THAT INCREASED MOLECULAR WEIGHT WOULD LEAD TO GREATER ANTIMISTING EFFECTIVENESS THUS ALLOWING USE OF LOWER CONCENTRATIONS TO ACHIEVE PERFORMANCE. GTA WAS NOT AWARDED THE CONTRACT. HOWEVER, NASA SPONSORED SIMILAR WORK AT THE UNIVERSITY OF CALIFORNIA, BERKELEY IN JUNE 1981. THE UNIVERSITY OF CALIFORNIA INVESTIGATORS REPORTED THAT B-230 WAS 3 TIMES AS EFFECTIVE AS FM-9 WHEN MEASURED IN THE FAA'S FLAMMABILITY TEST APPARATUS AND RECOMMENDED INVESTIGATING HIGHER MOLECULAR WEIGHT PIB.(2)

UNDER A PROGRAM FOR THE U.S. ARMY PERFORMED FROM MID-1981 THROUGH EARLY 1982, GTA EVALUATED THE RELATIVE ANTIMISTING EFFECTIVENESS OF ELEVEN DIFFERENT HIGH MOLECULAR WEIGHT ADDITIVES, INCLUDING THREE DIFFERENT MOLECULAR WEIGHTS OF PIB. THE HIGHEST MOLECULAR WEIGHT PIB GAVE THE BEST ANTIMISTING EFFECTIVENESS AND MOLECULAR WEIGHT DEPENDENCE WAS ESTABLISHED.(3)

FROM JANUARY THROUGH JULY 1983, GTA PRODUCED ANTIMISTING FUEL SAMPLES MODIFIED WITH A NEW, HIGHER MOLECULAR WEIGHT PIB, OPPANOL B-246, TO THE U.S. NAVY FOR GUNFIRE TESTS AT THE NAVAL WEAPONS CENTER, CHINA LAKE, CALIFORNIA, FOR SPINNING DISC TESTS AT THE NAVAL RESEARCH LABORATORY, FOR LABORATORY FLAMMABILITY TESTS AT THE UNIVERSITY OF CALIFORNIA, BERKELEY, AND FUEL SPECIFICATION TESTS AT THE NAVAL AIR PROPULSION CENTER, TRENTON, NEW JERSEY. THE UNIVERSITY OF CALIFORNIA TESTS CONFIRMED THE INCREASE IN EFFECTIVENESS OF THE HIGHER MOLECULAR WEIGHT PIB, DEMONSTRATING OVER 100 TIMES SUPERIORITY TO FM-9.(4) TWO OTHER RESULTS WERE SIGNIFICANT: 1) THE NAVY GUNFIRE TESTS - WHICH SUBJECTED THE FUEL

TO VERY HIGH SHEAR FORCES - DEMONSTRATED A BASIC CHANGE IN THE NATURE OF THE COMBUSTION OF JP-5 WHEN TREATED WITH 50 PARTS PER MILLION OF B-246; AND 2) THE NAVAL AIR PROPULSION CENTER CONCLUDED THAT JP-5 WITH 200 PARTS PER MILLION OR LESS OF ADDITIVE WAS WITHIN CURRENT FUEL SPECIFICATION LIMITS, WITH THE EXCEPTION OF GUM CONTENT. (5)

PARALLELING ITS FUEL RESEARCH GTA INVESTIGATED THE USE OF WATER SOLUBLE, HIGH MOLECULAR WEIGHT VISCOELASTIC POLYMERS TO PREVENT LOSSES BY DRIFT IN AGRICULTURAL CHEMICAL SPRAYING. IN THE SPRING AND SUMMER OF 1983, RESEARCH WAS CONDUCTED JOINTLY WITH STAUFFER CHEMICAL COMPANY AT THE DEPARTMENT OF AGRICULTURE'S RESEARCH CENTER AT TEXAS A&M AND AT THE UNIVERSITY OF DAYTON RESEARCH INSTITUTE. AT UDRI, VERY HIGH SPEED, LASER BACK-LIGHTED PHOTOGRAPHY WAS USED TO PHOTOGRAPH SPRAY PATTERNS. WE FOUND THAT THE MASS OF SUB 50 MICRON SIZED DROPLETS IN A SPRAY OF WATER WAS REDUCED BY 99% WITH ADDITION OF 12 PARTS PER MILLION OF THE ANTIMISTING ADDITIVE.

EARLIER THIS YEAR, GTA AND BASF MADE A DECISION TO JOINTLY INVESTIGATE THE POTENTIAL FOR VERY HIGH MOLECULAR WEIGHT PIB AS AN AVIATION FUEL ADDITIVE. THE FIRST RESULT OF WORK AT BOSCH GMBH IN GERMANY, INDICATES THAT THE DISCOVERIES MADE AT UDRI WITH WATER SPRAYS, -- THAT SUB 50 MICRON DROPLETS CAN BE SUBSTANTIALLY ELIMINATED WITH LOW CONCENTRATIONS OF HIGH MOLECULAR WEIGHT VISCOELASTIC ADDITIVE, -- EXTENDS TO JP-4 FUEL TREATED WITH OPPANOL B-246.

AT THIS POINT, I WOULD LIKE TO GIVE YOU THE REASONS WHY GTA AND BASF HAVE MADE THE DECISION TO INDEPENDENTLY PURSUE ANTIMISTING FUEL RESEARCH, AND WHY WE BELIEVE IT CAN LEAD TO THE OPERATIONAL USE OF AN EFFECTIVE AND INEXPENSIVE ANTIMISTING FUEL.

FIRST, ALL FLAMMABILITY TESTS IN WHICH HIGH MOLECULAR WEIGHT PIB HAS BEEN EVALUATED AND COMPARED WITH OTHER ADDITIVES HAVE DEMONSTRATED IT'S SUPERIORITY. DATA FROM THE UNIVERSITY OF CALIFORNIA, BERKELEY SHOWS B-246 TO BE MORE THAN 100 TIMES MORE EFFECTIVE IN SUPPRESSING IGNITION THAN FM-9.

SECOND, PIB, IN CONTRAST TO FM-9, IS EFFECTIVE IN SUPPRESSING FUEL MISTING UNDER HIGH SHEAR FORCES. THIS WAS DEMONSTRATED BY THE NAVAL RESEARCH LABORATORY IN 1981 IN A PROGRAM COMPARING OPFANOL B-200 WITH FM-9. (6) ONE OF NRL'S CONCLUSIONS WAS THAT "THE SUPERIOR PERFORMANCE OF POLYISOBUTYLENE OVER FM-9 IN ITS JET FUEL DISPERSIONS SUGGESTS ITS APPLICATION IN CASES WHERE EXTREMELY HIGH VELOCITIES MIGHT BE ENCOUNTERED"; FOR EXAMPLE, AS IN UNWANTED FUEL INGESTION IN JET ENGINES.

THIRD, PIB IS CHEMICALLY SIMILAR TO JET FUEL AND IS COMPATIBLE WITH AIRCRAFT FUEL AND FUEL SYSTEMS. TESTS PERFORMED FOR GTA AT AN INDEPENDENT FUELS TESTING LABORATORY ESTABLISHED THAT PIB IS BASICALLY COMPATIBLE WITH JET FUEL AND EXCEPT FOR VISCOSITY INCREASE AND GUM CONTENT, HAD LITTLE OR NO ADVERSE EFFECT ON FUEL

CHARACTERISTICS. THE FUEL TESTED WAS JET-A TREATED WITH 1,500 PARTS PER MILLION OF OPPANOL B-230. IN ADDITION, AS I SAID EARLIER, THE U.S. NAVAL AIR PROPULSION CENTER AT TRENTON, NEW JERSEY CONDUCTED FUEL SPECIFICATION ANALYSIS TESTS OF OPPANOL B-246 IN JP-5. THESE TESTS INDICATED THAT FUELS TREATED WITH 200 PARTS PER MILLION OR LESS OF THE ADDITIVE ARE WITHIN CURRENT FUEL SPECIFICATION LIMITS EXCEPT FOR EXISTENT GUM. AT 50 PARTS PER MILLION IT MET ALL SPECIFICATION LIMITS INCLUDING GUM CONTENT. (5)

FOURTH, PIB IS AN INEXPENSIVE, OFF-THE-SHELF POLYMER. COMPANY ESTIMATES INDICATE THAT ADDED COSTS PER GALLON OF FUEL WOULD BE LESS THAN ONE CENT, HOW MUCH LESS WOULD DEPEND UPON CONCENTRATION REQUIREMENTS.

FIFTH, SIMPLIFIED IN-LINE DISSOLVING OF OPPANOL B-246 HAS BEEN DEMONSTRATED USING A STORABLE, FAST DISSOLVING POWDER DEVELOPED BY GTA.

SIXTH, AND MOST SIGNIFICANT IN DECIDING TO PROCEED WITH OUR OWN RESEARCH PROGRAM, WE BELIEVE THAT EXPLOSIVE MIST FIRES CAN BE OVERCOME WITH VERY LOW CONCENTRATIONS OF B-246, DRAMATICALLY REDUCING COST AND OPERATIONAL OBJECTIONS TO FAST ANTIMISTING FUEL CANDIDATES. I WOULD LIKE TO SPEND MORE TIME DESCRIBING THIS PHENOMENON BECAUSE OF THE IMPACT IT HAD ON OUR DECISION TO MOVE FORWARD.

OUR INTEREST IN DIFFERENTIATING EXPLOSIVE FIRES FROM OTHER MIST INDUCED FIRES WAS THE RESULT OF SEVERAL SEPARATE INPUTS. IN PREPARING A PROPOSAL TO THE U.S. NAVY TO EVALUATE THE EFFECTIVENESS OF B-246 AGAINST GUNFIRE INDUCED FUEL FIRES, WE DISCOVERED A REPORT OF WORK PERFORMED IN 1974 AT THE AIR FORCE AERO PROPULSION LABORATORY.(7) THE RESEARCH REPORTED WAS AN EVALUATION OF THE EFFECTIVENESS OF ANTIMIST FUEL ADDITIVES IN THE PREVENTION OF AIRCRAFT FUEL TANK ULLAGE FIRES AND EXPLOSIONS. IN THAT TEST PROGRAM, 50 CALIBER APJ PROJECTILES WERE FIRED INTO TANKS PARTIALLY FILLED WITH JET FUEL. PRESSURE MEASUREMENTS WERE MADE TO ASSESS THE STRUCTURAL DAMAGE TO BE EXPECTED FROM A PARTICULAR EVENT. BOTH NEAT AND TREATED FUELS WERE TESTED. IT WAS FOUND THAT ALTHOUGH THE VISCOELASTIC ADDITIVE DID NOT REDUCE THE PERCENTAGE OF IGNITIONS, IT DID DRAMATICALLY REDUCE THE PRESSURE RISE EXPERIENCED WITH NEAT FUEL. THE REPORT CONCLUDES THAT ANTIMIST ADDITIVES CAN EFFECTIVELY CONTROL FUEL TANK EXPLOSIONS.

THE NAVY AWARDED A CONTRACT TO GTA TO EVALUATE THE EFFECT OF HIGHER MOLECULAR WEIGHT PIB, B-246, ON SUPPRESSING MIST FIRE EXPLOSIONS FROM GUNFIRE. THIS PROGRAM PRODUCED TWO IMPORTANT SETS OF DATA. FIRST, THE UNIVERSITY OF CALIFORNIA, BERKELEY, A SUBCONTRACTOR, DISCOVERED THAT THE IGNITION OF MISTED JP-5 FUEL COULD BE MODIFIED SIGNIFICANTLY WITH AS LITTLE AS 3 PARTS PER MILLION OF B-246. SECOND, THE GUNFIRE TESTS PRODUCED PHOTOGRAPHIC EVIDENCE THAT FUEL MODIFIED WITH 50 PARTS PER MILLION OF B-246 DRAMATICALLY CHANGED THE

COMBUSTION BEHAVIOR OF JP-5. UNFORTUNATELY, DATA COLLECTION AT CHINA LAKE WAS LIMITED TO PHOTOGRAPHS USING A 400 FRAME PER SECOND CAMERA. SUBSEQUENT ANALYSIS OF THIS RESULT CONVINCED GTA AND BASF THAT THE VERY HIGH SHEAR FORCES FROM PROJECTILE PENETRATION OF THE NEAT JP-5 SAMPLE PRODUCED A LARGE POPULATION OF VERY FINE DROPLETS. THE RESULTING COMBUSTION WAS CHARACTERIZED BY AN EXPLOSIVE FORMATION OF A LARGE BLACK CLOUD ALMOST TOTALLY OBSCURING A LARGE FIREBALL. THE ADDITION OF 50 PARTS PER MILLION OF B-246 SIGNIFICANTLY REDUCED FINE ATOMIZATION OF THE FUEL, PRODUCING A MORE SLOWLY DEVELOPING, NON-EXPLOSIVE FIRE.

FOLLOWING THESE TESTS, GTA DID A BASIC REVIEW OF THE RELATIONSHIP BETWEEN COMBUSTIBILITY OF LIQUID MISTS AND MIST DROPLET SIZE. AS A RESULT, WE FOUND THAT IT IS WELL ESTABLISHED THAT DROPLETS ABOVE 40 MICRONS BURN RELATIVELY SLOWLY FROM DROPLET TO DROPLET WHILE THOSE BELOW 10 MICRONS BURN LIKE A VAPOR, WITH POTENTIALLY EXPLOSIVE FORCE.(8) IGNITION OF THE VAPOR IS SO FAST THAT THE LARGER DROPLETS ARE ROBBED OF OXYGEN, RESULTING IN PARTIAL COMBUSTION AND THE LARGE CLOUDS OF BLACK SMOKE WE OBSERVED.

GTA'S REVIEW ALSO INCLUDED STUDIES CONDUCTED AT THE CITY COLLEGE OF NEW YORK IN THE 1960'S IN WHICH DROPLET FORMATION IN JET SPRAYS WAS STUDIED WITH AND WITHOUT ADDITION OF A VISCOELASTIC ADDITIVE.(9) ONE OF THE DISCOVERIES MADE WAS THAT HIGHER CONCENTRATIONS OF ADDITIVE, WHILE SIGNIFICANTLY INCREASING THE MEAN DROPLET DIAMETER, CREATED A BIMODAL DISTRIBUTION OF DROPLET SIZE,

WITH A LARGE NUMBER OF VERY SMALL DROPLETS. THIS WAS THE RESULT OF THE DROPLET BREAK-UP PHENOMENON WHEREBY THE STRONGLY VISCOELASTIC SOLUTION WOULD FORM A RIGID STRAND BETWEEN LARGER SEPARATING DROPLETS, WHICH WOULD FRACTURE FORMING THE FINE DROPLET SEGMENT OF THE SPRAY. WITH LOWER CONCENTRATIONS OF ADDITIVE, THEIR PHOTOGRAPHS SHOWED THAT THE WEAKER VISCOELASTIC FORCE PRODUCED A STRAND BETWEEN DROPLETS WHICH CONTRACTED INTO THE LARGER DROPLETS AS IT WAS STRETCHED. THE BIMODAL DISTRIBUTION WAS NOT PRESENT AND THE VERY FINE DROPLETS DISAPPEARED.

AS A RESULT OF THIS REVIEW, WE DECIDED THAT IT WAS IMPORTANT TO OBTAIN MORE PRECISE DATA ON THE EFFECT OF LOW CONCENTRATIONS OF A HIGH MOLECULAR WEIGHT ADDITIVE ON DROPLET SIZE OF SPRAYED LIQUIDS. WE WERE FAMILIAR WITH THE UNIVERSITY OF DAYTON RESEARCH INSTITUTE'S CAPABILITIES WITH HIGH SPEED PHOTOGRAPHY AND ARRANGED FOR A PROGRAM TO TAKE HIGH SPEED LASER BACK LIGHTED PHOTOGRAPHS OF AQUEOUS SPRAYS. A VERY HIGH MOLECULAR WEIGHT WATER SOLUBLE POLYMER WITH VISCOELASTIC PROPERTIES SIMILAR TO B 246 WAS CHOSEN FOR THE TESTS. THE RESULT WAS STARTLING TO BOTH UDRI AND GTA. MORE THAN 99% OF ALL DROPLETS BELOW 50 MICRONS WERE ELIMINATED WITH A TREATMENT OF 12 PARTS PER MILION OF THE ADDITIVE.

IT SEEMED REASONABLE TO CONCLUDE IN LIGHT OF WHAT WE HAD OBSERVED THAT FINELY ATOMIZED DROPLETS, UNDER 50 MICRONS, ARE RESPONSIBLE FOR EXPLOSIVE IGNITION OF MISTED FUEL AND THAT THIS VERY FINE DROPLET FORMATION, EVEN UNDER HIGH SHEAR CONDITIONS, CAN BE

SUPPRESSED WITH A LOW CONCENTRATION OF A HIGH MOLECULAR WEIGHT VISCOELASTIC ADDITIVE. USE OF LOW CONCENTRATIONS OF OPPANOL B-246 TO SUPPRESS EXPLOSIVE MIST FIRES WAS SEEN BY BOTH GTA AND BASF TO OFFER SIGNIFICANT POTENTIAL FOR INCREASING AIRLINE PASSENGER SAFETY.

IN SUMMARY, A COMBINATION OF THE FOLLOWING FACTORS POINT TO THE POSSIBILITY OF USE OF HIGH MOLECULAR WEIGHT PIB AS AN ANTIMISTING FUEL ADDITIVE FOR COMMERCIAL AIRLINE OPERATIONS:

- \* SATISFACTORY EFFECTIVENESS AT VERY LOW CONCENTRATIONS
- \* SATISFACTORY EFFECTIVENESS UNDER HIGH SHEAR FORCES
- \* COMPATIBILITY WITH CURRENT FUEL SPECIFICATIONS AND UNMODIFIED FUEL SYSTEMS
- \* LOW COST, AND CURRENTLY UNDER HIGH VOLUME PRODUCTION
- \* EASE OF HANDLING AND APPLICATION
- \* ELIMINATION OF CATASTROPHIC FUEL EXPLOSIONS

IN THE IMMEDIATE FUTURE, GTA AND BASF INTEND TO JOINTLY CONDUCT A SERIES OF TESTS IN GERMANY AND IN THE UNITED STATES TO VERIFY RESULTS OF PRIOR LIMITED TESTS, SHOWING THE ANTIMISTING BEHAVIOR OF LOW CONCENTRATIONS OF HIGH MOLECULAR WEIGHT PIB AND THE RESULTING SUPPRESSION OF CATASTROPHIC FUEL EXPLOSIONS. HOPEFULLY, THIS WILL ACCELERATE THE REALIZATION OF IMPROVED AIRPLANE CRASH SURVIVABILITY.

## REFERENCES

1. U.S. Department of Transportation, Federal Aviation Administration, Technical Center, Aircraft Research and Technology for Antimisting Kerosene Conference, Report No. FAA-CT-81-1 (June 1981).
2. Kapelke, M.S., "The Anti-Flammability Effectiveness of Polymers in Jet Fuel". Report to NASA, Ames Research Center under Grant No. NCC 2-140 (1981).
3. Hadermann, A.F., Waters, P., Trippe, J.C., and Weitzen, W., "Investigation of the Application of a Cryogenic Blending Process to Produce Antimisting Diesel Fuels", Final Report (January 1982).
4. Williams, M.C., "Evaluation of Antimisting Fuels", Report to Naval Research Laboratory under NRL contract N00173-83-M-3279 (June 1983).
5. Hadermann, A.F., and Trippe, J.C., "Antimisting Aviation Fuels Research and Development", Final Report, U.S. Navy Contract No. N00140-83-M-2403 (October 1983).
6. Little, R.C., and Pratt, R., "The Effect of Additives on the Aerosolization of JP-5 Jet Fuel", NRL Memorandum Report 4694 (August 1982).
7. Clodfelter, R.G., and Gandee, G.W., "Evaluation of the Effectiveness of Antimist Fuel Additives in Prevention of Aircraft Fuel Tank Ullage Fires and Explosions", Technical Report AFAPL-TR-73-111 (January 1974).
8. Von Elbe, L, Combustion, Flames and Explosions of Gases, Second Edition 1961.

## FIRE PREVENTION ON AVIATION FUELS

### DUE TO ACCIDENTAL SPILLAGE OR IMPACT CONDITIONS

by Robert Gordon Bayless

Ladies and gentlemen, I am presenting this as a concept paper in the area of explosion control for aircraft crashes.

In the latter part of 1984, an expose on television demonstrated the effectiveness of a "safe" fuel for aircraft crash conditions. As many of you might remember, the results were not as expected. The plane exploded after a brief delay. Because of the tremendous loss of human life as the result of airplane crashes, CSI set out to find a procedure for controlling the explosion potential of gasoline and/or aviation fuels in the event of a crash.

It is well a well-known fact that in the event of an airplane crash, fuel fumes are released and when they come into contact with a spark, an explosion results that kills the passengers.

We believe we may have the beginnings of a solution to this problem through a process that almost completely prevents the vapors from escaping upon impact. Through this process it may be possible to minimize the chance of an explosion and allow many more human lives to be spared.

Microencapsulation is the process of enclosing a chemical substance inside a bubble composed of a polymer coating. The chemical composition of the polymer can control how and when the "payload" inside the capsule is released.

We have been able to use our process to encapsulate UP-4 jet fuel and white gasoline (Coleman fuel).

In microencapsulating gasoline, we have demonstrated the capability of nearly eliminating the existence of the vapor.

Let me show you a demonstration:

(pour out uE white gasoline - light match and demonstrate)

In order to understand the magnitude of this capability,  
consider the following:

The standard characteristics of fuels are:

Vapor Pressure of JP-4 is about 2-3 PSI at 100°F

Vapor Pressure of Gasoline about 7-15 PSI at 100°F

Flash Point: 15°

On thermogravimetric analysis, the measurements on uE white  
gasoline were:

Slow loss of weight up to 17% of original weight to 190°C

From 190°C to 200°C, the weight loss was rapid, up to  
90% of the remaining capsule weight.

At 280°C, the total residue weight was 4% meaning 96%  
of the capsule weight is the "payload" inside.

In addition, our capsules can be controlled to a diameter  
size as small as one micron or as large as 2,000 microns, with  
standard deviation of  $\pm 30\%$ . The optimal size and distribution  
will have to be determined.

There are several questions that come to mind when addressing  
this concept. Some of these are;

- 1) Can the capsule walls give added BTU?
- 2) How do we liquify on demand?
- 3) How do we achieve maximum packing density of this  
solid? (uE converts liquids to solids)

The determination of answers to each of these and other similar  
questions are Research and Development projects in themselves. We  
have some ideas and plans for resolving these issues, given adequate

funding. However, in order to start any project, we need a basic hypothesis: i.e. microencapsulation can contribute to fire safety.

In summary, microencapsulation of fuels offers the following benefits:

1. prevention of release of volatile vapors which could allow explosion
2. control of combustion to slow burning
3. safe recovery of accidentally spilled fuel with a minimum of damage to the ecosystem.

As I first stated, this is a CONCEPT paper. Given the ability to nearly eliminate the vapor, can this technology be used to prevent fire or explosion caused by spillage or impact?

I have spent 22 years, including the last 12 years as chief scientist of Capsulated Systems, Inc., developing and perfecting microencapsulation technology.

Because of the fact that the volatile nature of the fuels is the cause of explosions and a threat to human life, I strongly feel that I can use my experience in microencapsulation to minimize volatility, therefore providing a possibly safe solution, to the danger of aircraft fuel spillage.

# JET FUEL VISCOSITY AT LOW TEMPERATURES WITH NOTES ON n-ALKALINE CRYSTALS

by Dr. Dale Schruben

## ABSTRACT

The experiment portion of this study developed apparatus and procedures to collect jet fuel viscosity versus temperature data for temperatures down to about (-60°C) in a manner that was compatible with prior jet fuel data bases generated with the Brookfield viscometer.

Viscosity data showed good reproducibility even at temperatures a few degrees into the two-phase region. The correlation portion of the study indicated that the viscosity-temperature relationship could be correlated by two linear segments when plotted as a standard log-log type representation (ASTM D 341). The breakpoint between the high and low temperature line segments is the filter flow temperature, a fuel characteristic approximated by the freezing point. A generalized correlation appears sufficiently accurate for many design or performance calculations.

In the low temperature two-phase region, wax precipitation is significant. Qualitative literature were quantitatively analyzed along with data in this study to plot crystal size versus composition for the fuel model  $C_{20}$ - $C_{24}$ n-alkane system in solvent. This simple model suggested that wax mixtures tend towards smaller crystal sizes than pure wax species. Complex mixtures in jet fuels lead to two-phase states, at least in some instances, that have small enough crystals to be treated as a continuum.

## INTRODUCTION

Hydrocarbon jet aviation fuels (petroleum based and synthetic [1]) now contribute, and will contribute vitally to defense and transportation. All the while, economic and strategic incentives tend towards fuels with higher freezing temperature behavior. This can have a consequence on viscosity at low near-freezing temperatures. Related question have been a concern for some time since Maxwell Smith, in his classic book on aviation fuel [3], relates that cold use of fuel and its relation to viscosity was one of the early problems of aviation fuel development history. Strawson [4] reviewed this topic in a larger rheological context

by showing the impact of non-Newtonian aspects such as thixotropy on fuel storage and forwarding to the engine. Pass, et al. [5] (their Figure 9) showed a viscosity vs. temperature plot that is very much like a modern ASTM viscosity vs. temperature (D-341) chart [6]. Particularly significant, in the work of Pass [5] was the identification of two low-temperature regions dependent on the degree of precipitation of wax constituents: a wax free region and a colder region where wax contributes to a greater viscosity increase per cooling increment. Wax precipitation in the fuel can affect more than just the shear viscosity. Ford and Robertson [7] of Shell discussed a fuel flow test where a cold sample experience sudden gravitational body forces, yet does not flow. These tests define a low temperature criterion, holdup. Behavior can become complex, as found by Dimitroff, et al. [8] in a perceptive study of fuels in the high-viscosity temperature region. They recognized three generic types of behavior, any one of which a given fuel might manifest:

- a gradual increase in viscosity as the whole fuel sample gelled, due to n-alkanes in a network structure, but not as crystals.
- the sharp break in the viscosity vs. temperature relationship at a point where distinct wax crystals form a solid phase.
- a distinct region of increased viscosity as two liquid phases formed (though not the great increase in viscosity noted in the first case where the second phase was a solid).

This work has found the second "sharp break" generic behavior to be the most common in an experimental and correlative study of jet fuel viscosity over temperatures covering a range from ambient down to those associated with the two-phase state. Since a limited number of fuels could be studied, they were selected to be representative of current and future jet fuels, while encompassing typical high and low viscosity behaviors. Study of such fuels by capillary viscometry can encounter difficulties with wax crystals

restricting flow in the viscometer tube at low temperatures. However, shear viscosities can still be measured if the geometry of the shear flow field is large compared to the wax crystal geometry. In this study, the Brookfield shear viscometer was chosen because it met that geometric constraint and because of the success of prior measurements reported in the appendix of a report by Stockemer [2]. Standard ASTM methods guided the reduction and display of data and formed the basis of a generalized correlating method that might be useful for design purposes.

#### SAFETY

Low temperatures can be experienced on long, high altitude or polar flights, where fuel flowability in the wing tank itself, independent of the fuel forwarding system, becomes a concern. Appropriate viscosity data could help predict the convective currents that can develop as a jet wing tank is slowly cooled. These currents, in turn, bear importantly on fuel flowability, and hence safety, if temperatures drop below the fuel freezing point and solids form. If the solids are somewhat fluidized in those currents, they flow usefully. However, as precipitates on the tank bottom, those solids could interfere with fuel usage by several mechanisms. Below the freeze point in the two-phase region viscosity data would be useful to the designer of aircraft wing-tank, pump, and fuel forwarding lines to assure they perform their function safely. A related question, use of additives for performance or safety improvement at normal temperatures, should be considered in the light of possible influence on viscosity and cold flow at low temperatures.

#### APPARATUS

The Brookfield viscometer was selected in order to be compatible with prior data bases, for example, Stockemer [2]. It was combined with a cold chamber to make an apparatus that gives reliable shear viscosity data at temperatures from 20°C to -80°C.

Figure 1 shows the inside of the cold chamber (Messimer Model

FT4-100x350, capable of sustaining temperatures to  $-135^{\circ}\text{F}$ ). The three-legged stand (only two legs are shown in the schematic) rests on a flat plate level on the bottom of the cold chamber and supports a platform that holds the viscometer cup. Nuts on the upper threaded portion of the legs allow the platform to be tilted. A standard 6 inch Brookfield extension shaft for the viscometer penetrates the top of the cold chamber and mounts the spindle that turns in the cup. The cold chamber top is about 3 inches thick and the fiber insulation in it serves as a seal. A plexiglass piece with a notch a little larger than the shaft provides further sealing.

Alignment of cup, spindle, shaft, and viscometer on top of the cold chamber was difficult and required one person on top of the chamber observing a near zero scale deflection on the viscometer for a known low viscosity standard (e.g. toluene) while another person carefully adjusted the platform. These difficulties were minimized when the platform was aligned using a notch in the back of the platform to mount the cup flush with the platform. The cup was held flush with a retaining wire. Cured elastomer bonded the legs to the bottom of the inside of the cold chamber. This stabilized the platform and also dampened vibrations so that consistently reproducible viscosity data were obtained.

Figure 2 shows the insulated window with glove mainly made out of styrofoam and plexiglass. The laminate structure (Figure 3) with two panes of plexiglass allows the volume between the two panes to be purged with dry air or nitrogen, should frost cause visibility problems. So far, purge has not been necessary.

Limited capillary viscometer results (not reported herein) were used for spot checks of the Brookfield viscometer results. The capillary viscometer, visible through the window in Figure 3, has a thermocouple placed in the actual fuel sample in it. Good visibility assures accurate viscosity readings. The rubber tube attached to the top of the capillary viscometer exits the chamber to a vacuum bulb. Fuel sample can be drawn up the capillary, even at low temperature, as long as the cold section of the rubber tube inside the cold chamber is not required to flex. In addition, the

cold fuel sample cannot have significant wax structures in it or it will plug the capillary. The visual and manual capability inside the cold chamber suggests other operations could be done such as cold blending or pumping tests.

### PROCEDURE

The typical experimental run involved obtaining the viscosity at a given temperature and then lowering the sample temperature anywhere from 5 to 20°C for the next viscosity-temperature determination. About an hour was allowed for the new quasi steady-state temperature to be obtained after a change in the temperature control setting.

Temperature measurements were routinely taken by a thermocouple submerged in actual test fuel at the top of the spindle-cup assembly and by two glass thermometers resting in a test fuel surrogate of approximately equivalent thermal mass to that of the test fuel itself. These thermometers were read through a plexiglass port in the cold chamber, as was another glass thermometer that hung freely in the cold chamber. These temperatures were occasionally checked against fuel temperature by dipping a thermometer in the top of the cup, then removing the spindle and dipping a thermometer in the bottom of the cup. Such cautionary measures verified that the one hour allowed after a set point change was more than adequate to insure thermal equilibrium. The copper-constantan thermocouple was linked by a custom high accuracy Rochester Instrument transmitter to a MOTOROLA 6800 microprocessor. A special transmitter was obtained calibrated for our temperature range of 30°C to -100°C.

For calibration purposes the Brookfield viscometer was considered an instrument that gives only scale deflection,  $s$ , at a given angular velocity,  $\omega$ . Since scale deflection is directly proportional to viscosity,  $\eta$ , and  $\omega$ , the following can be written for an unknown (un) test liquid and a standard:

$s_{un} = \eta_{un} \omega$ ,  $s = \eta \omega$ , or

$$\eta_{un} = \frac{s_{un}}{\omega} \left( \eta \frac{\omega}{s} \right)$$

The quantity in parenthesis is considered a calibration factor,  $F$ . Mean values of  $F$  were determined through measurements with suitable standards. Toluene provided calibration in the 0 to 10 portion of the scale range over the study temperature range of 20°C to -80°C. Sucrose solution provided calibration over the full 0 to 100 scale range, depending on  $\omega$ , but only at about 20°C. However, isopropyl alcohol covered the deflection range as well as the temperature range.

The equation

$$\log n = 1141.35 (1/T - 1/324.12) \quad (1)$$

for isopropanol from page 444 of the text by Reid, Prausnitz and Sherwood [9] was used ( $\log$  is base 10,  $T$  in K, e.g.  $n = 1.75$  cp @ 30°C). This reference shows that this relation is accurate to within a few percent over a large portion of our study temperature range.

An example of the determination of the calibration factor is shown in Table 1, which gives results at a series of angular velocities for isopropanol at -8.7°C. The reference viscosity,  $n$  at this temperature is 6.23 ( $10^{-3}$ ) Pa·s (Pa·s =  $10^3$  cp), from Equation (1). Hence the calculated value of  $F$  from the mean value of  $\langle s \rangle / \omega$  is  $6.23/0.09290 = 67.1$ .

At each temperature sufficient number of scale deflections,  $s$ , were observed (usually less than 5) to obtain what was judged to be a representative sample. Values of  $F$  by this procedure were fairly consistent and had an overall average of  $F = 69.8$ .

Data rejections were usually done by showing that the rejects fell outside a 95% confidence interval (based on the non-reject data). However, some rejections appeared obvious without the detailed check, particularly at low angular velocities, where fluid mechanical stabilization was less active to counteract surface tension and pendulum effects that tend to higher torques on the spindle than those due purely to shear stress.

For the experimental program, eight fuel samples were selected to be representative of present and potential future jet fuels, and at the same time, to suggest typical high and low viscosity behaviors. Table 2 presents available freeze point, filter flow point, viscosity, and density data for the eight fuels selected for study.

## RESULTS AND DISCUSSION

For each of the eight fuels studied, an extensive set of determinations of viscosity as a function of temperature and shear rate were made. Table 3 is an example of a typical series of measurements, summarizing the viscosity for LFP-3 fuel at 10.6°C over a range of shear rates. Except at the two lowest rates where the Brookfield viscometer scale barely deflects, the dynamic viscosity was independent of the shear rate. This was to be expected at the higher temperatures where the fuels showed ideal, Newtonian behavior. At lower temperatures, where wax precipitation occurs, viscosity showed greater variation and may depend somewhat on the shear rate. Table 4 is an example of a typical series of measurements at low temperatures. The range of viscosities used in finding the average (as determined by the highest minus the lowest divided by the lowest) is 6% for Table 3, but 12% for Table 4. The clearest evidence for non-Newtonian behavior was displayed when the shear rate was increased then immediately decreased, with slight differences in viscosity. In addition to shear history, thermal history effects were observed.

The averaging techniques improve the Brookfield determinations by averaging out undesirable statistical behavior such as compensation for zero shift. For example, scale deflections do not always return to zero after each run. The averaged scale deflections and shear rate-averaged viscosities smooth the random zero shifts without necessity for readjustment of the apparatus after each determination.

For comparison with typical aviation fuel characteristics, this study reports kinematic viscosities. The kinematic viscosities are the shear rate-averaged dynamic viscosities from the Brookfield viscometer divided by fuel density. Density was measured at selected temperatures for each fuel by the author. Interpolation of temperature-related densities was achieved using a correlation furnished by C. Moynihan of Rennselaer Polytechnic Institute. In SI units a centipoise times  $10^{-3}$  converts to pascal second (Pa·s) and a centistoke times  $10^{-6}$  converts to metre<sup>2</sup> per second (m<sup>2</sup>/s).

Experimental results of the kinematic viscosities of the eight fuels as functions of temperature are plotted on ASTM D-341 charts (ref. 6) in figures 4 to 11 (Plots on actual size Chart I ASTM D-341 paper are available from the author). The data are plotted on coordinates based on the relationship

$$\log \log (\nu + 0.7) = A + B \log T$$

where  $\nu$  = kinematic viscosity, m<sup>2</sup>/s  $\times 10^6$  (cSt)

T = temperature, K

A, B = constants.

On these coordinates hydrocarbon viscosities will plot linearly with temperature for convenience in interpolating and extrapolating limited laboratory measurements. That property of the ASTM D-341 chart is also useful for a generalized correlation to be discussed.

The eight experimental fuels represent a range of present and proposed jet fuels, encompassing properties from the kerosene to distillate (Diesel) ranges. They have differing amounts of wax content and would be expected to have quite different viscosity characteristics. Nevertheless, the experimental data in figures 4 to 11 shown by the circles can all be reasonably represented by a fit to a linear correlation consisting of two line segments. The low temperature, high viscosity region has a higher slope on the plots, that is, viscosity increases more rapidly with decreasing

temperature than at the higher temperatures. This region of the plot includes temperatures at which the fuel has appreciable wax precipitation. The shear-rate averaged viscosities in this two phase region, however, can be reasonably represented linearly, in the same manner as the higher-temperature, Newtonian viscosities.

The intersection of the two solid line segments for each fuel was established as the filter flow temperature (ref. 10). The slopes of the two solid line segments represent the best fit to the data passing through the common, filter flow temperature, point. The filter flow temperature, ASTM D-4305, is measured as the temperature where flow resumes through a filter upon rewarming from a colder "no flow" condition. This temperature provides a fundamental basis for distinguishing between the two viscosity regimes since it is determined from what is in effect, a viscosity-dependent procedure. The filter flow temperature for typical aviation turbine fuels is zero to 2°C colder than the visual freezing point (ref. 10 and also note Table 2). In figures 4 to 11, the filter flow temperature, shown as the intersection of the two correlating solid segments, corresponds to viscosities of 12 to 20 x 10<sup>6</sup> m<sup>2</sup>/s (cSt) for most of the fuels. Two exceptions are LFP-11 (fig. 7), and LFPA-1 (fig. 10), where the filter flow temperature corresponds to viscosities near 30 x 10<sup>6</sup> m<sup>2</sup>/s. These fuels have the lowest wax contents of all the experimental fuels.

While the viscosity-temperature values in each of the plots (figure 4 to 11) are different, the slopes of the correlating segments do not vary greatly. This can be seen in fig. 12, where correlating lines from three fuels spanning a range of viscosity vs. temperature behaviors are shown to illustrate the spread of the slopes of the data fitting lines. It seems as if the slopes of this intermediate behavior might represent the entire fuel set with small deviations. This figure suggests that a generalized correlation constructed as a single set of two line segments (with slopes nearly the same as the middle set in the figure, actually derived by considering all fuels) would represent typical fuel behavior with acceptably small deviations. In figure 12, the

temperature axis is normalized with respect to the filter flow temperature, which forms a common break point between high and low viscosity regions, but viscosity is not normalized. Thus the correlations are aligned on the temperature axis, but they may deviate in slope and viscosity. However, the slopes of all the fuels fall within a range of negative 30 to 40 degree angles from the horizontal for the low viscosity region; and a range of negative 60 to 80 degree angles for the high viscosity region.

The similarity of slopes when normalized about a common break point form the basis of a generalized correlation. The purpose of the generalized viscosity temperature correlation is to provide a basis for prediction of fuel viscosity over a temperature range with only limited measurements. This correlation requires the following:

- 1) the parametric plot, obtained as a ASTM D-341 chart,
- 2) a single measurement of kinematic viscosity at a convenient temperature,
- 3) the filter flow temperature (ASTM D-4305), or, as an alternative, an estimate of this temperature as 1°C lower than the freezing point.

The procedure to construct the correlation begins by fixing the viscosity (item 2 above) on the D-341 chart (item 1). Then a line from that viscosity and temperature point is drawn at negative 35° slope until it intersects the viscosity at the filter flow temperature (item 3). From that intersection a line is drawn at a negative 70° slope to represent the low temperature viscosity behavior.

The generalized correlation was applied to assess its effectiveness as a fit to the data for the eight experimental fuels. This correlation is shown by the broken lines in figures 4 to 11. The line segments were determined by the procedure above and by a single measurement of viscosity made by a capillary viscometer for each fuel. This measurement is shown as a square data point in figures 4 to 11.

In the high temperature regions the generalized correlation (broken lines) agrees well with the data correlations (solid lines). In the low temperature regions, the generalized correlation deviates from the data. If a measurement of error is defined as the correlation line minus the data line divided by the data line value, the maximum of that measurement is about 30% for the high temperature region and about 200% for the low temperature region. Often an adjustment of the single viscosity measurement, shown by the square point, by no more than one cSt could shift the correlation to reduce the apparent error considerably.

As summarily regards low temperature viscosities, a group of eight present and potential future aviation turbine fuels have been studied. Viscosities were correlated with temperature by two linear segments on a D-341 chart, one in the cold two-phase region, and one in the normal liquid phase region.

Use of the correlation requires a single viscosity characteristic (at ambient temperature, if necessary) and an estimate of the filter flow temperature (derived from the freezing point). Thus fuel viscosities that cannot be measured can be estimated by the generalized correlation. This prediction would be valuable and sufficiently accurate for many purposes, for example in designs of aircraft fuel systems for storage, heat transfer, and pumpability at low temperatures. Next, the solid phase in the cold two-phase region is considered in more detail.

Wax crystal size can directly determine whether it will pass through a filter. If it is small enough to pass, shape and perhaps texture could still strongly influence the ability of the crystal to stick to the surface of the wires that make up the filter screen. Other surfaces the cold wax-solvent mixture might contact could similarly capture the wax particle, depending on morphological aspects like size and shape.

The first morphological question addressed was to relate size to composition. The simple, easily managed system of  $C_{20}$  and  $C_{24}$  n-alkane to make 5% total in heptane was the starting model. Photographs of wax crystals in the literature for near model systems were available, but only at concentrations of pure  $C_{20}$ ,

pure  $C_{24}$ , and a 50/50 mixture totalling 5% in solvent [12]. This size data was collected from the photographs and plotted.

Size versus composition data at other compositions was desired. The "Seta-point" or filter flow apparatus (Figure 13) was used as the apparatus in which the crystals were grown. Although the sample chamber was not designed for photography, a Nikon F with a "macro" close up lens was mounted to the view port (Figure 13) to take the photograph shown in Figure 14. For clarity, a line drawing of Figure 14 was made as shown in Figure 15 to serve as a key. By use of the key and photo, the crystal can be identified; and knowledge of the scale allowed its size to be determined. Size was taken to be the length of the longest chord in the crystal. By this technique, the size versus composition plot could be constructed for the  $C_{20}$ - $C_{24}$  system in heptane at variable compositions.

Figure 16 shows that pure  $C_{20}$  and pure  $C_{24}$  in heptane can grow to lengths on the order of a few millimeters. However, intermediate compositions result in crystals much smaller. The long n-alkane chains crystallize with their axes perpendicular to the growing crystal plane. However, when different species (different chain lengths) are crystallizing together, pieces of the chain can appear above the crystal plane. Perhaps these act as steps to start new crystal growth which could detract from the growth of large planes and tend to smaller crystals [13]. This suggests complex mixtures, involving a distribution of n-alkane waxes as in a jet fuel, could tend towards smaller wax crystal size.

An unusual event occurred in work with the "seta-point" apparatus, that illustrates how the complex wax mixtures in a jet fuel can have such small crystals that continuum models for transport processes are justified. The event of formation of a cold fuel film laden with small wax crystals was recorded as in Figure 17. The cooling cycle of the apparatus happened to be arrested and normal operation that would have interfered with the film did not act so that the film was essentially free falling under gravity. Fortunately a time sequence could be recorded and a composite of those photographs is illustrated in Figure 18.

The initial mathematical model for describing this transport action of a falling film of high viscosity with a temperature gradient across it is illustrated in Figures 19 and 20. It could be described as a classical falling film only with a linear viscosity variation across it due to the temperature profile in the film. This is of course a continuum model where discrete crystals, or crystal size distribution play no roll in the continuously varying viscosity. The model has been further developed [14]. To the degree the model has had some success, it illustrates the validity of continuum methods in dealing with transport processes in wing tanks. The more fundamental the chemical knowledge of factors in a wing tank as they make up the physical state, the more thorough the application of physical transport processes, the more accurate will be the performance prediction, the better will be the design, and the safer will be the aircraft.

## REFERENCES

- [1] Friedman, R. "High-Freezing Point Fuels Used for Aviation Turbine Engines", manuscript No. 79-GT-141, presented at Gas Turbine Conference and Exhibit and Solar Energy Conference, ASME, San Diego, CA, March 12-15, 1979.
- [2] Stockemer, F. J., "Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model", NASA CR-159615, May 1981.
- [3] Smith, Maxwell, "Aviation Fuels", G.T. Foulis and Co. Ltd., Henry-on-Thames, 1970.
- [4] Strawson, H., "The Pumpability of Aviation Turbine Fuels at Low Temperatures", J. Inst. Petrol., 45, (1959), pp. 129-137.
- [5] Pass, F. J.; Csoklich, C.; Wastl, K., "Solid Paraffins and Low Temperature Characteristics of Petroleum Products", 7th World Petroleum Congress, Proceedings, Vol. 8, Elsevier, New York, 1967, pp. 129-139.
- [6] ASTM D 341-77, "Standard Viscosity-Temperature Charts for Liquid Petroleum Products", Annual Book of ASTM Standards, Vol. 05.01 A.S.T.M., Philadelphia, 1985.
- [7] Ford, P. T.; Robertson, A. G., "Jet Fuels-Redefining the Low Temperature Requirements", Shell Aviation News, No. 441, July 1977, pp. 22-26.
- [8] Dimitroff, E.; Gray, J. T.; Meckel, N. T.; Quillian, R. D., "Crystal-Liquid Fuel Phase Intersolubility and Pumpability", 7th World Petroleum Congress, Proceedings, Vol. 8, Elsevier, New York, 1967, pp. 142-155.
- [9] Reid, R. C.; Prausnitz, J. M.; Sherwood, T. K., "The Properties of Liquids", 3rd Edition, McGraw-Hill, New York, 1977.
- [10] ASTM D 4305-83, "Test Method for Filter Flow of Aviation Fuels at Low Temperature", Annual Book of ASTM Standards, Vol. 05.03, A.S.T.M., Philadelphia, 1985.
- [11] ASTM D 2386-84, "Test Method for Freezing Point of Fuels", Annual Book of ASTM Standards, Vol. 05.02, A.S.T.M., Philadelphia, 1985.

- [12] Holder, G. A. and Winkler, J. J., "Wax Crystallization from Distillate Fuels", Inst. Pet., 51, 228 (1965).
- [13] Halter, E.; Kanel, J.; and Schruben, D. L., "Growth Rate for  $C_{24}$  n-Alkane Crystal in Heptane", Liq. Fuel Tech., 3, 477 (1985).
- [14] Schruben, D. L., "Ripple in Falling Film", Chemical Engineering Education, to appear.

1 Report No. NASA CR-174911		2 Government Accession No.		3 Recipient's Catalog No.	
4 Title and Subtitle Measurement and Correlation of Jet Fuel Viscosities at Low Temperatures				5 Report Date August 1985	
				6 Performing Organization Code	
7 Author(s) Dale L. Schruben				8 Performing Organization Report No. None	
				10 Work Unit No.	
9 Performing Organization Name and Address The University of Akron Department of Chemical Engineering Akron, OH 44325				11 Contract or Grant No. NAG 3-488	
				13 Type of Report and Period Covered Contractor Report	
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546				14 Sponsoring Agency Code 505-40-22	
15 Supplementary Notes Final report. Project Manager, Robert Friedman, Aeropropulsion Facilities and Experiments Division, NASA Lewis Research Center, Cleveland, Ohio 44135.					
16 Abstract Apparatus and procedures were developed to measure jet fuel viscosity for eight current and future jet fuels at temperatures from ambient to near -60°C by shear viscometry. Viscosity data showed good reproducibility even at temperatures a few degrees below the measured freezing point. The viscosity-temperature relationship could be correlated by two linear segments when plotted as a standard log-log type representation (ASTM D 341). At high temperatures, the viscosity-temperature slope is low. At low temperatures, where wax precipitation is significant, the slope is higher (viscosity increasing rapidly with temperature). The breakpoint between temperature regions is the filter flow temperature, a fuel characteristic approximated by the freezing point. A generalization of the representation for the eight experimental fuels provided a predictive correlation for low-temperature viscosity, considered sufficiently accurate for many design or performance calculations.					
17 Key Words (Suggested by Author(s)) Fuels                      Freezing point Jet fuels                  Shear viscometry Viscosity				18 Distribution Statement Unclassified - unlimited STAR Category 28	
19 Security Classif. (of this report) Unclassified		20 Security Classif. (of this page) Unclassified		21 No. of pages	
				22 Price*	

Table 1.  
SHEAR VISCOSITIES FOR ISOPROPANOL CALIBRATION  
 $T_{\text{fuel}} = -8.7^{\circ}\text{C}$

$\omega$ (rpm)	s	$\langle s \rangle$	$\langle s \rangle / \omega$
1	0.2	0.2	0.2
2.5	0.25	0.25	0.1
5	0.4, 0.6, 0.6, 0.4	0.5	0.1
10	0.75, 0.75, 0.9, 0.9	0.825	0.0825
20	1.75, 1.75, 2.2, 1.8	1.875	0.09375
50	4.4, 4.6, 4.5, 4.5	4.5	0.09
100	9.2, 9.2, 8.8, 9.25	9.112	<u>0.09112</u>
	reject (0.2)		$\langle \langle s \rangle / \omega \rangle = 0.09290$

Table 2.  
PROPERTIES OF EXPERIMENTAL FUELS

Code No.	Type	Freezing Point Temperature, °C	Filter Flow Temperature, °C	Viscosity, <sup>a</sup> m <sup>2</sup> /s(cSt), at given temp., °C	Density kg/m <sup>3</sup>	Density <sup>b</sup> coefficient kg/(m <sup>3</sup> °C)
LFP-3	Diesel	-16.6	-19	■ 13.1 @ -12 2.58 @ 38	838.3	-.711
LFP-6	No.2 <sup>c</sup>	-28.0	-29.1	■ 16.5 @ -23.5 10.6 @ - 6.5	857.0	-.689
LFP-9	Jet	-44.5	-44.5	■ 5.2 @ -20 2.9 @ 6	810.7	-.706
LFP-11	Jet	-45.0	-45.8	■ 3.96 @ 0 4.0 @ 6	842.7	-.710
LFP-14	No.2 <sup>c</sup>	-32.6	-35.3	■ 3.74 @ 0 3.6 @ 6	819.7	-.704
LFPA-1	Jet	-47.1	-49.1	2.5 @ 19 ■ 3.3 @ 5	797.4	-.711 <sup>d</sup>
LFPA-4	Jet	-40.5	-38.5	■ 3.0 @ 6	789.7	-.711 <sup>d</sup>
Shale II JP-5		-48.5	-50.2	■ 2.8 @ 6 21 @ -16	799.7	-.711 <sup>d</sup>

<sup>a</sup> The viscosity used in the generalized prediction correlation is taken from this table and indicated by a square (■) here and in Figures 4 through 11. Sources of data are Stockemer [2], unpublished measurements of NASA-Lewis Research Center, and this study.

<sup>b</sup> For example, LFP-3 density at -20°C is  $838.3 - .711(-20^{\circ}\text{C}) = 852.5$ .

<sup>c</sup> Equivalent to a light heating oil, not finished, collected at refinery intermediate streams.

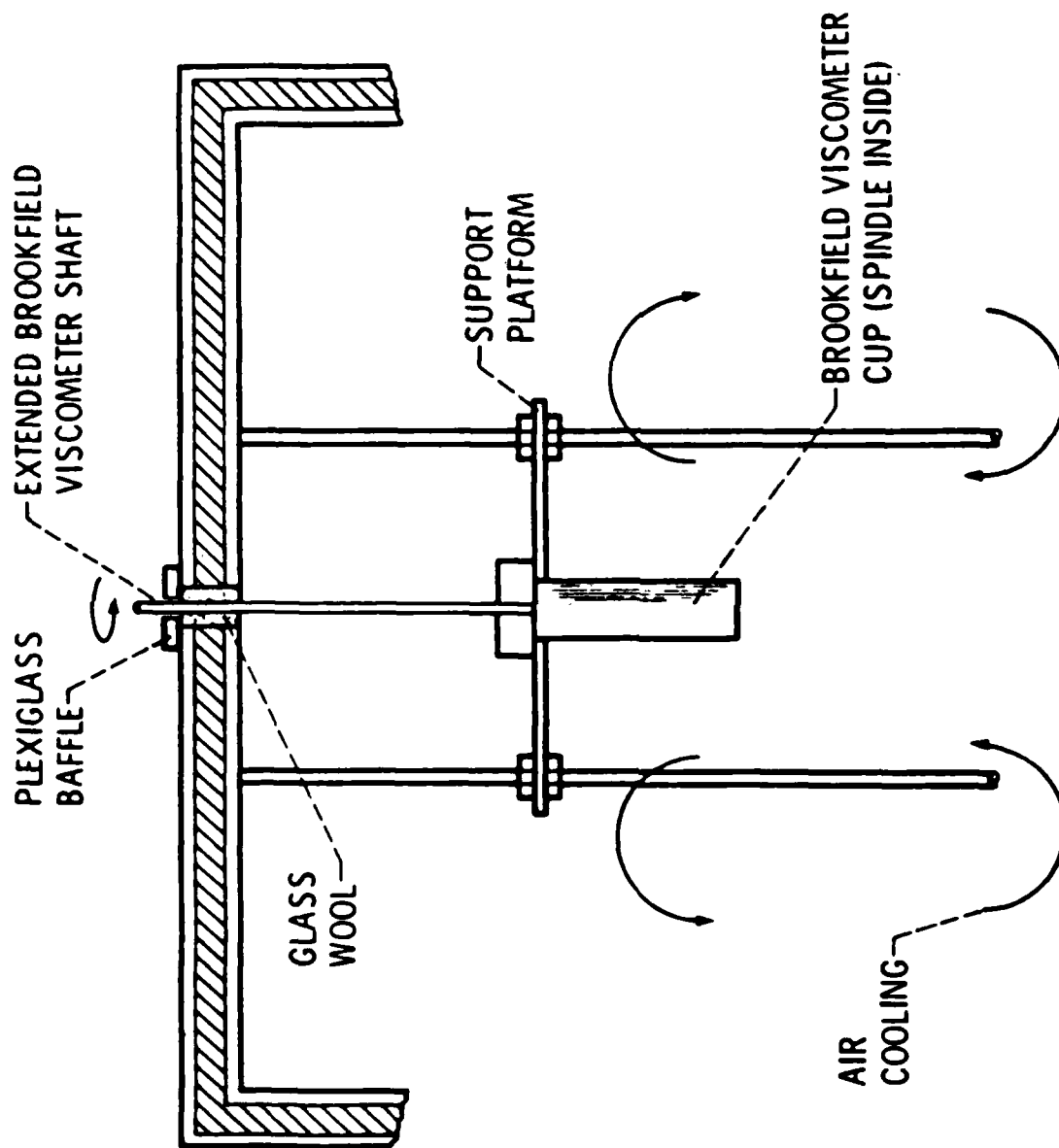
<sup>d</sup> Recommended coefficient based on unpublished data available at NASA-Lewis.  $\text{Density}(T) = \text{Density}(0^{\circ}\text{C}) + \text{correction factor} \times T$ ,  $T$  = fuel sample temperature, (°C).

Table 3  
TYPICAL SERIES OF LOW-VISCOSITY MEASUREMENTS  
LFP-3 Fuel at 10.6°C

$\omega$ (rpm)	s	$\langle s \rangle$	$\langle s \rangle / \omega$	$\eta$
1	0	0	0	0
2.5	0.2	0.2	0.08	5.58
5	0.2, 0.25, 0.25, 0.5	0.3	0.06	4.19
10	0.6, 0.6, 0.6, 0.6	0.6	0.06	4.19
20	1.1, 1.1, 1.1, 1.1	1.1	0.055	3.84
50	2.75, 2.75, 2.75, 2.75	2.75	0.055	3.84
100	5.6, 5.6, 5.75, 5.6	5.638	0.05638	<u>3.94</u>
	reject(0.08)			$\langle \eta \rangle_{\omega} = 4.00$

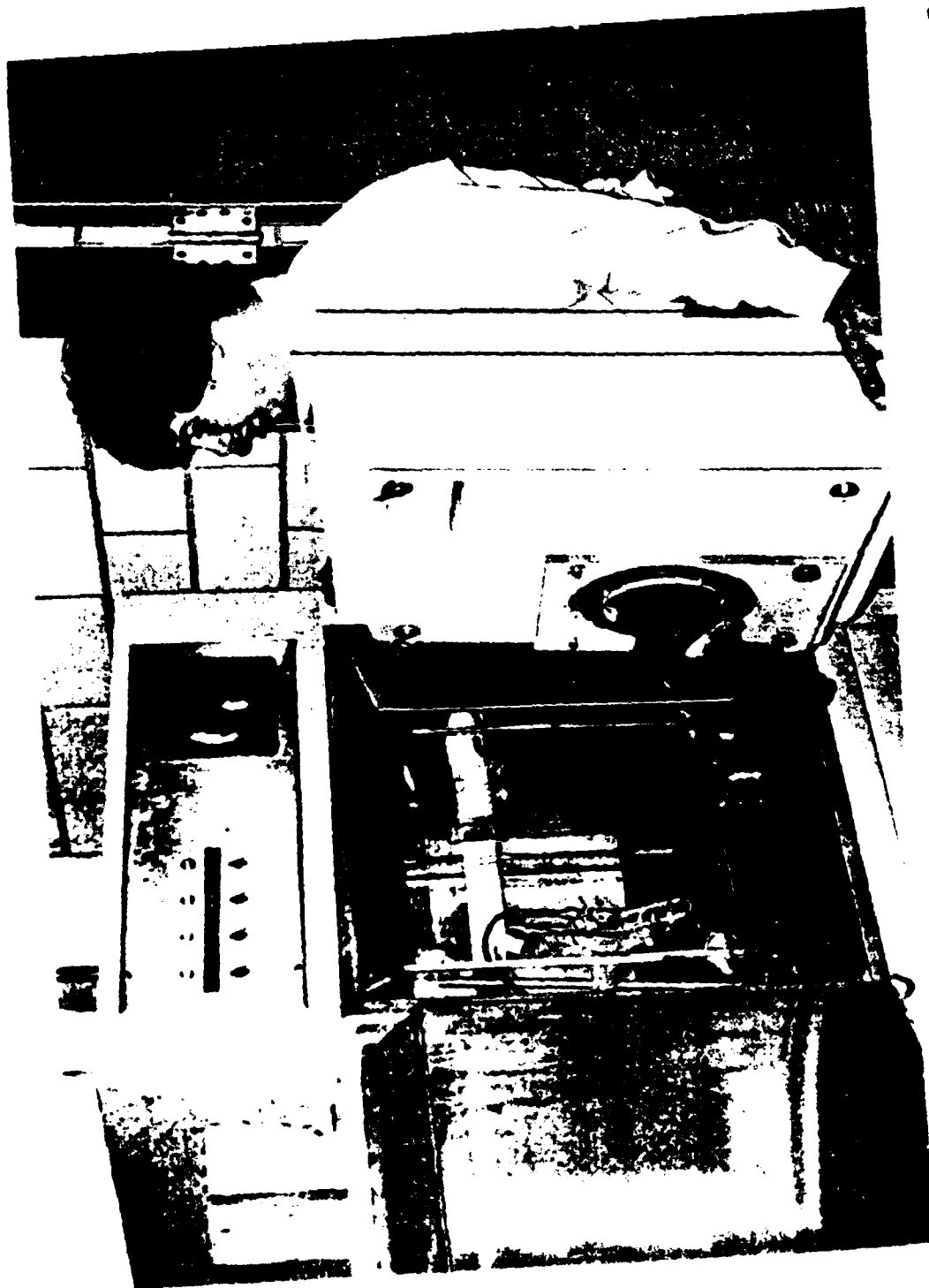
Table 4  
TYPICAL SERIES OF HIGH VISCOSITY MEASUREMENTS  
LFP-3 Fuel at -36.3°C

$\omega$ (rpm)	s	$\langle s \rangle$	$\langle s \rangle / \omega$	$\eta$
1	2.75	2.75	2.75	192
2.5	7.5	7.5	3	209
5	14.75	14.75	2.95	206
10	28.75, 27.75, 26.2, 28.25	27.74	2.77	194
20	53.0, 53.25, 54.2, 54.2	53.66	2.68	187
50	off scale			
$\langle \eta \rangle_{\omega} =$				197



CS-85-0704

Figure 1. Schematic of the inside of the cold chamber with viscometer accessories.



CS-85-0632

Figure 2. Cold chamber apparatus with window and glove.

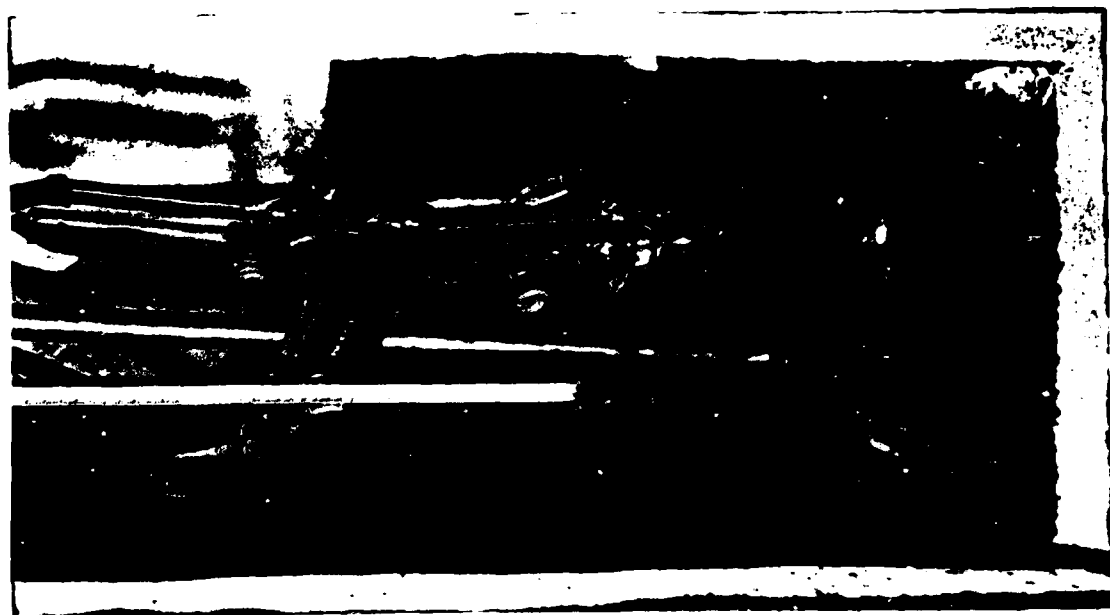


Figure 3. View showing laminate window structure and capillary viscometer.

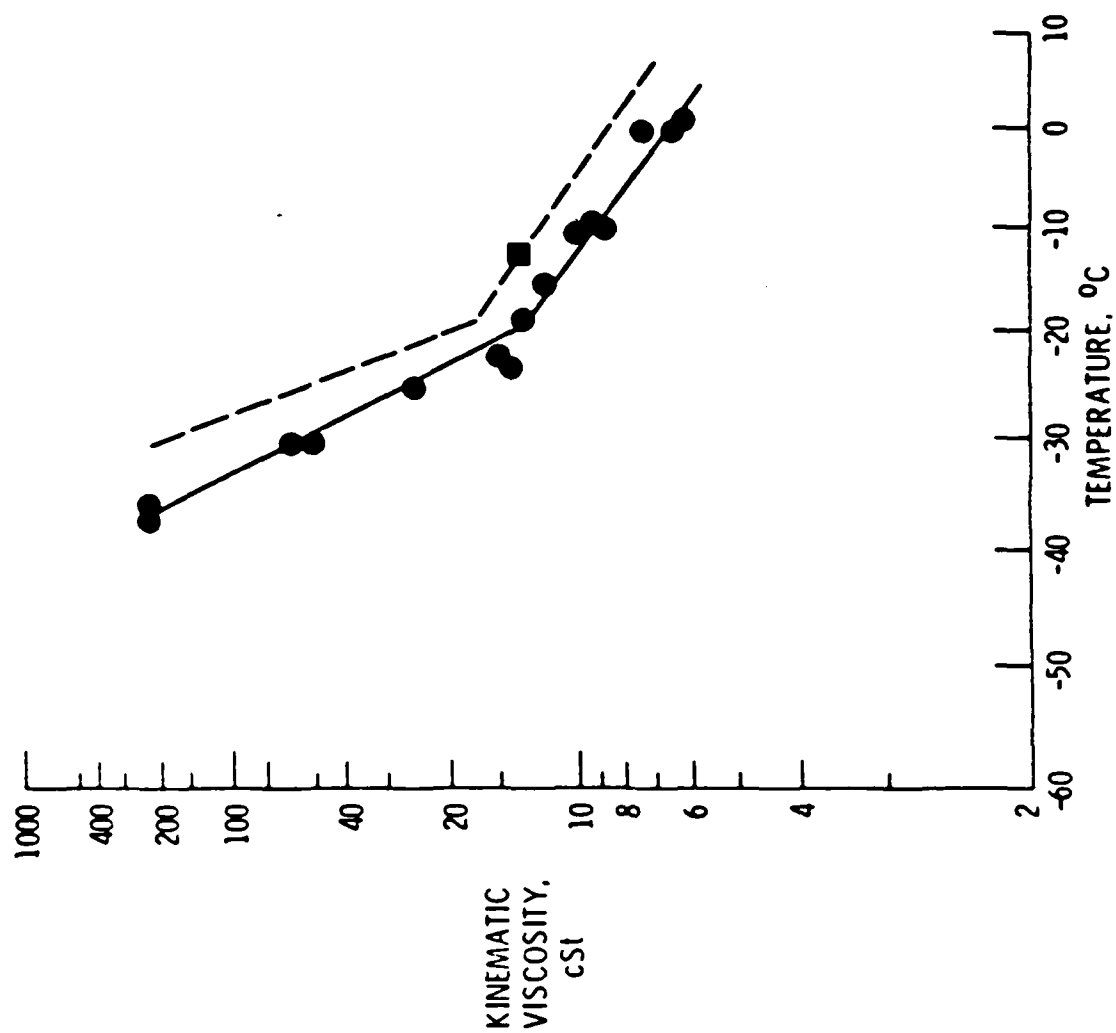


Figure 4. Viscosity data (—) and correlation (---) for fuel LPP-3.

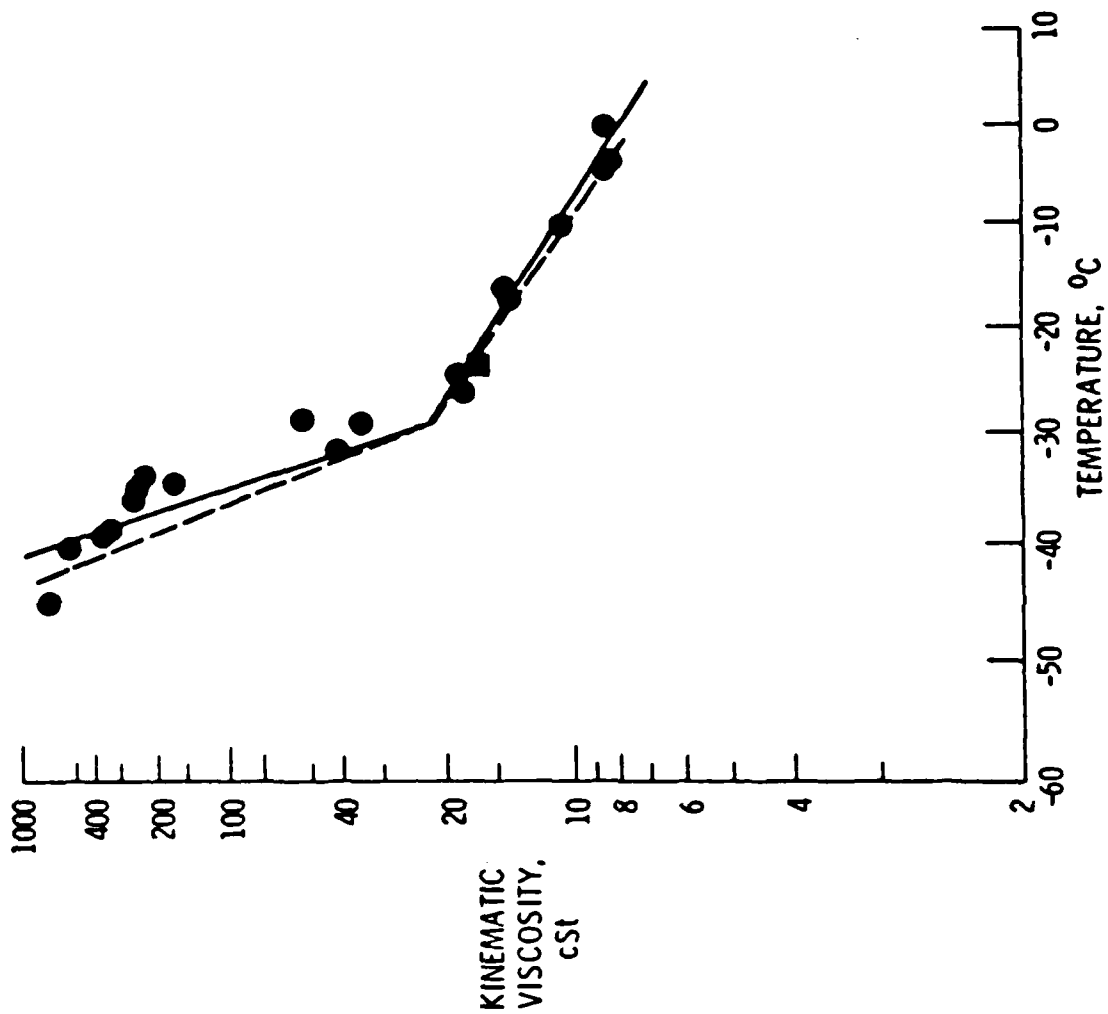


Figure 5. Viscosity data (—) and correlation (---) for fuel LPP-6.

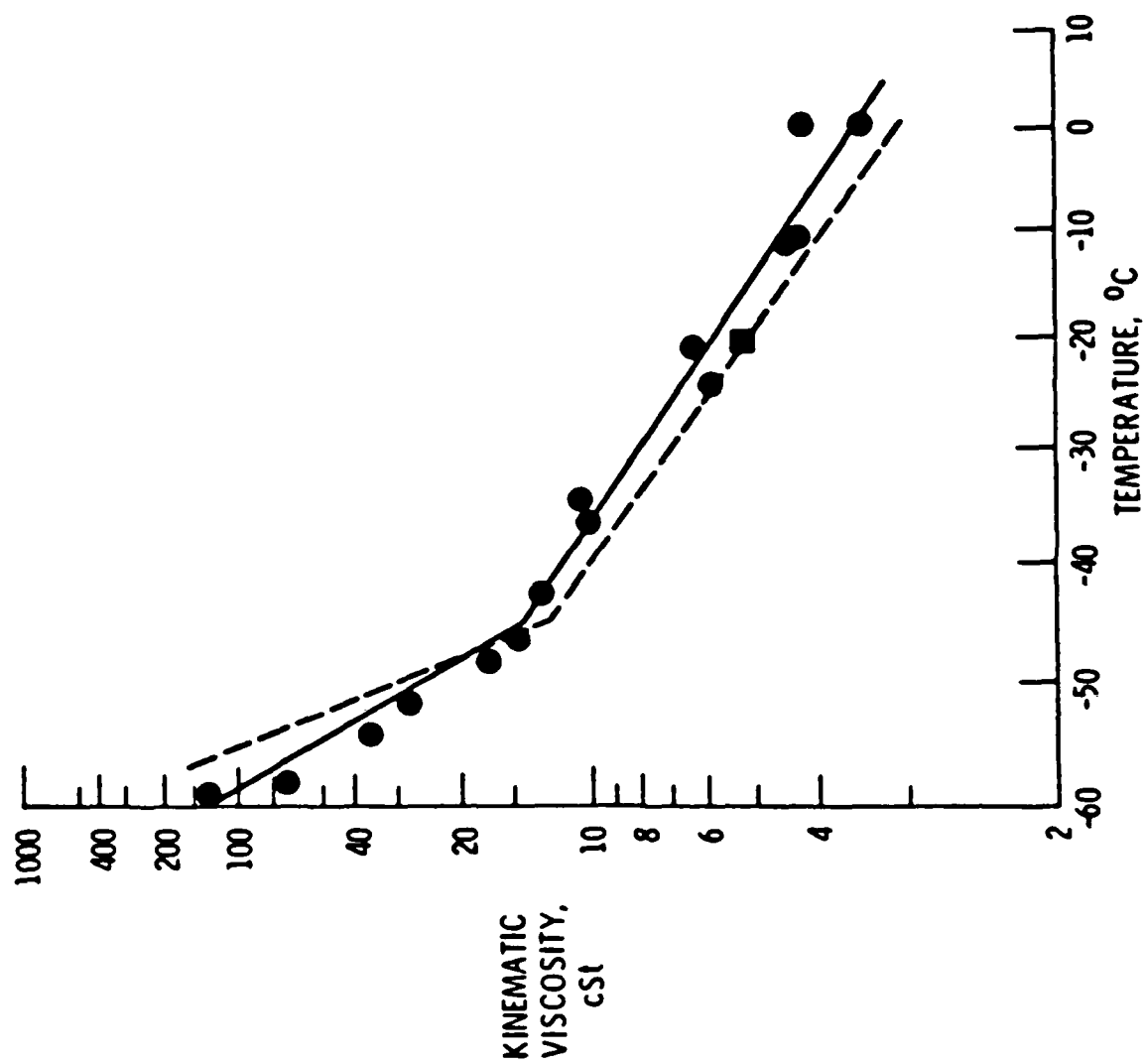


Figure 6. Viscosity data (—) and correlation (---) for fuel LPP-9.

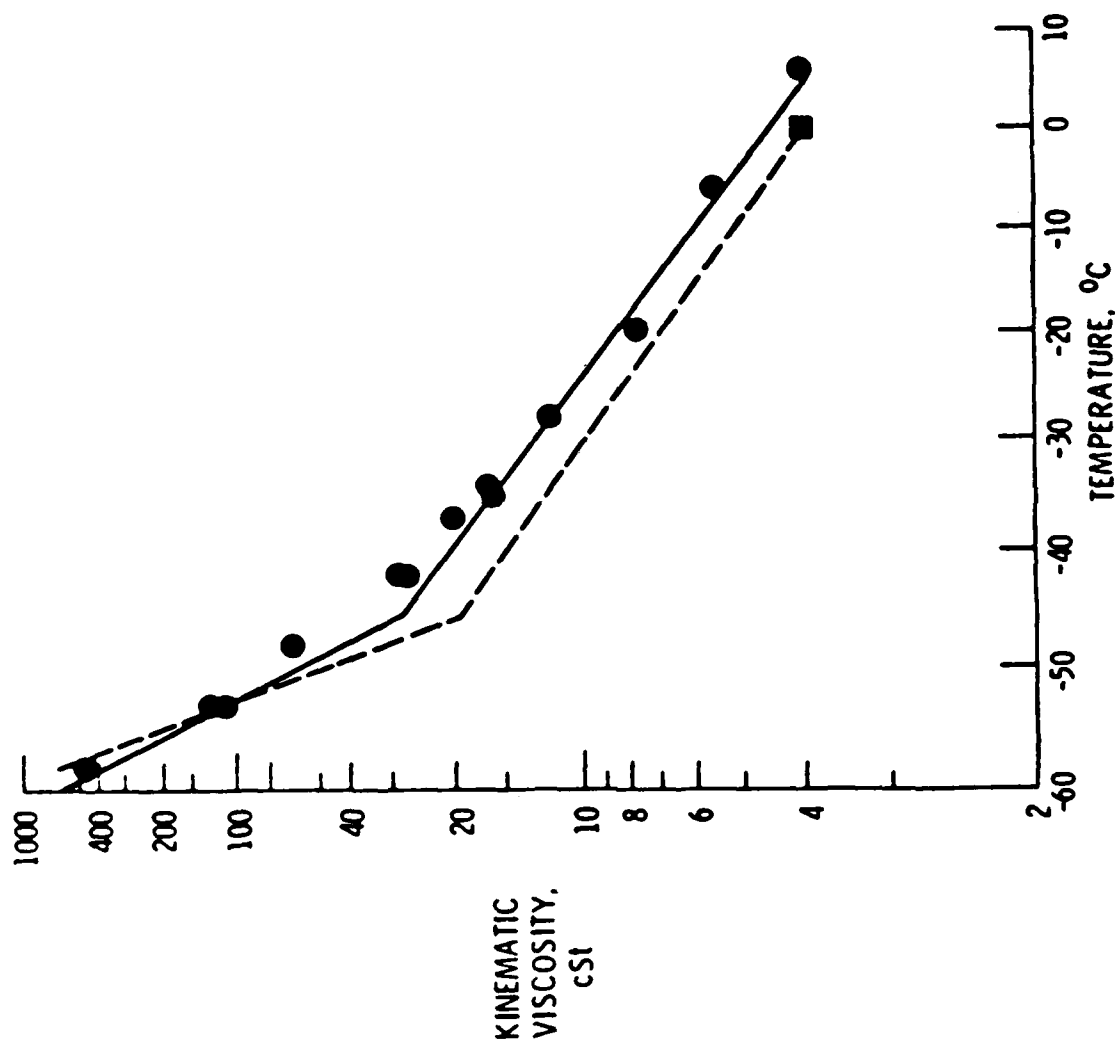


Figure 7. Viscosity data (—) and correlation (---) for fuel LPP-11.

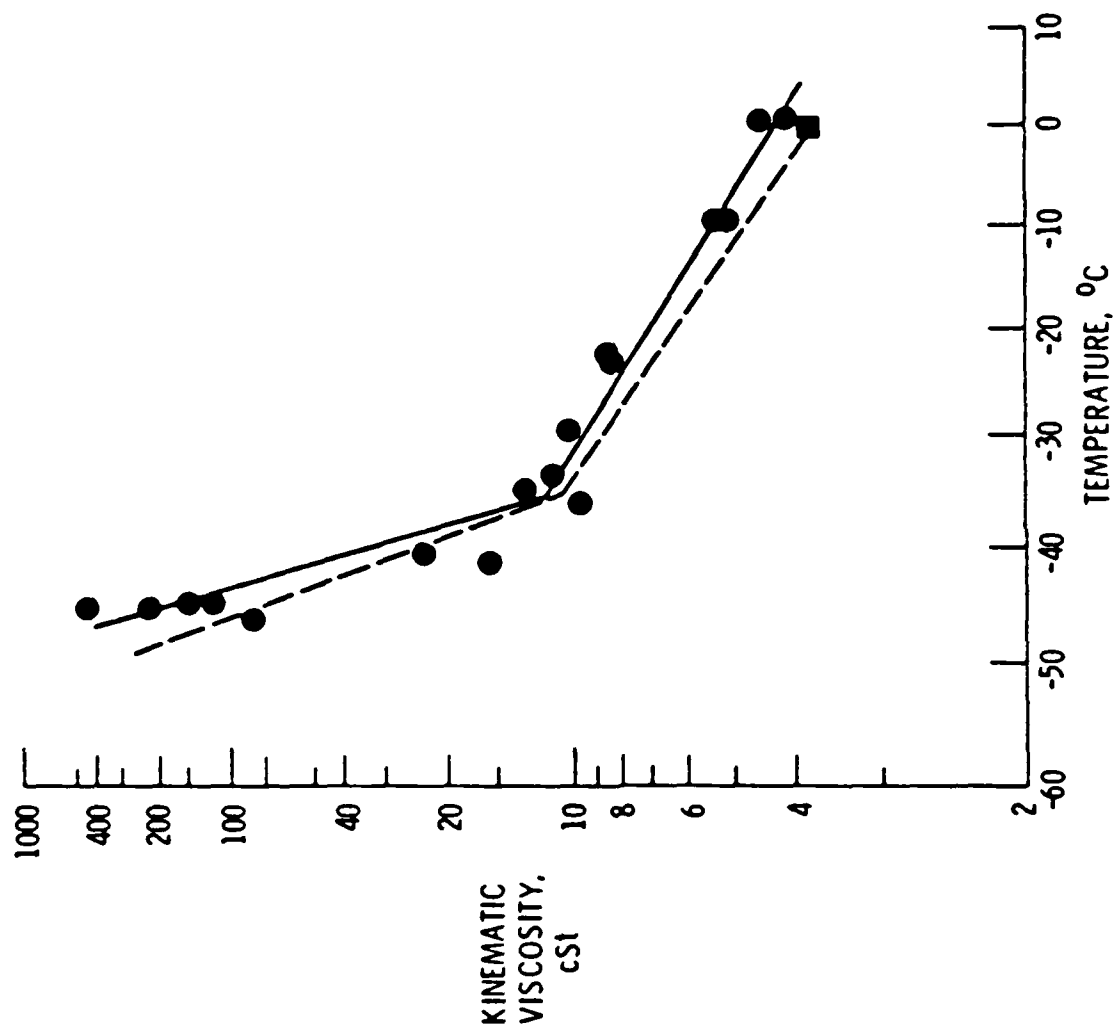


Figure 8. Viscosity data (—) and correlation (---) for fuel LPP-14.

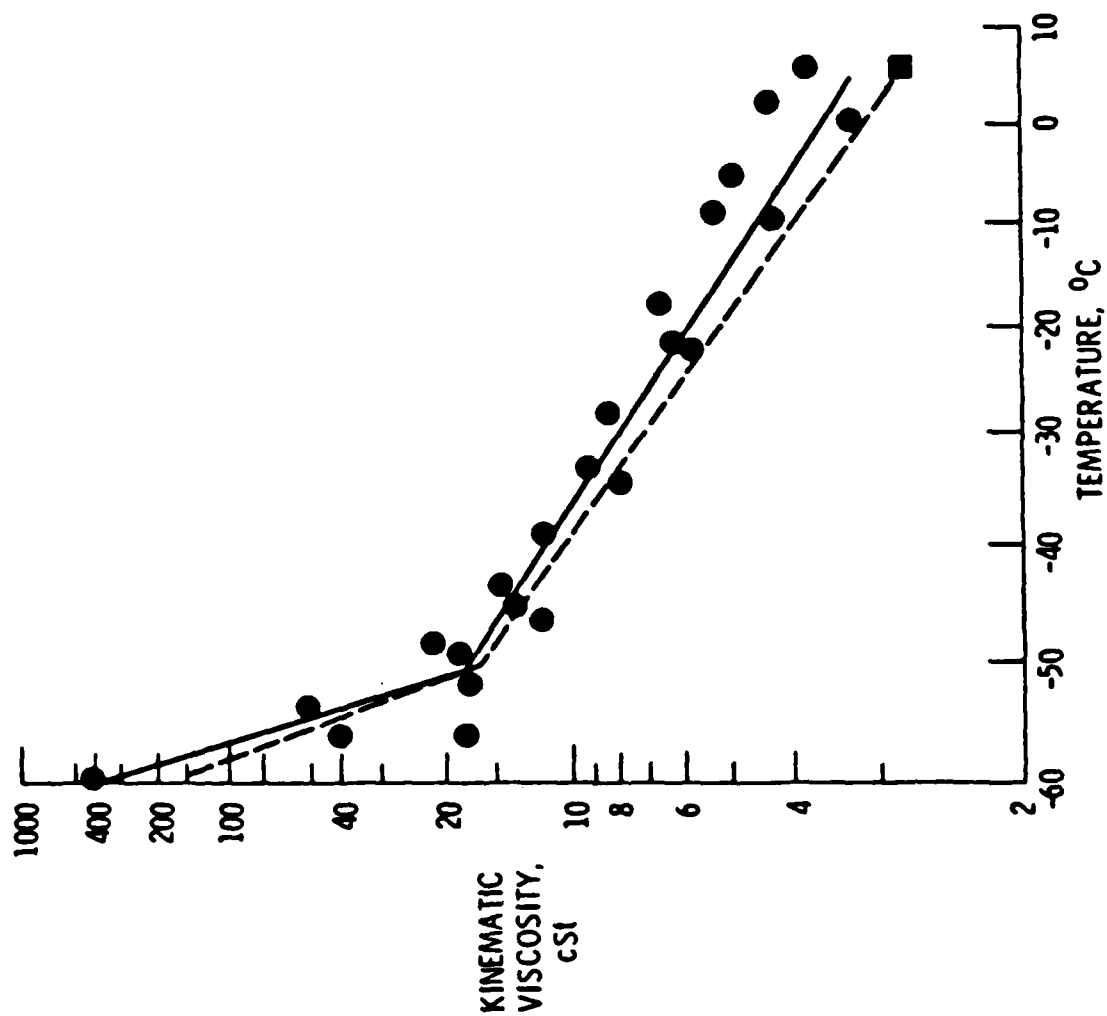


Figure 9. Viscosity data (—) and correlation (---) for fuel Shale II JP-5.

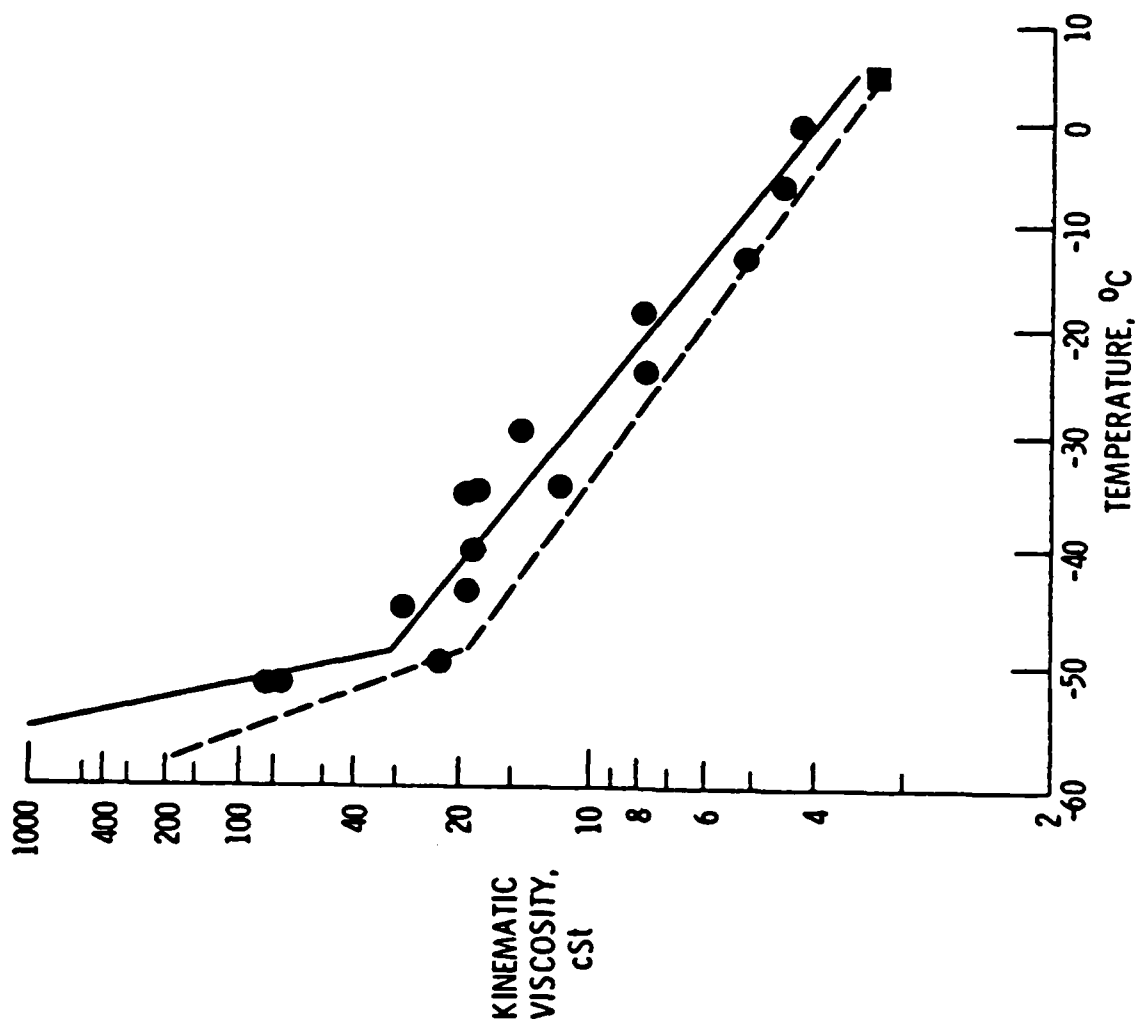


Figure 10. Viscosity data (—) and correlation (---) for fuel LFPA-1.

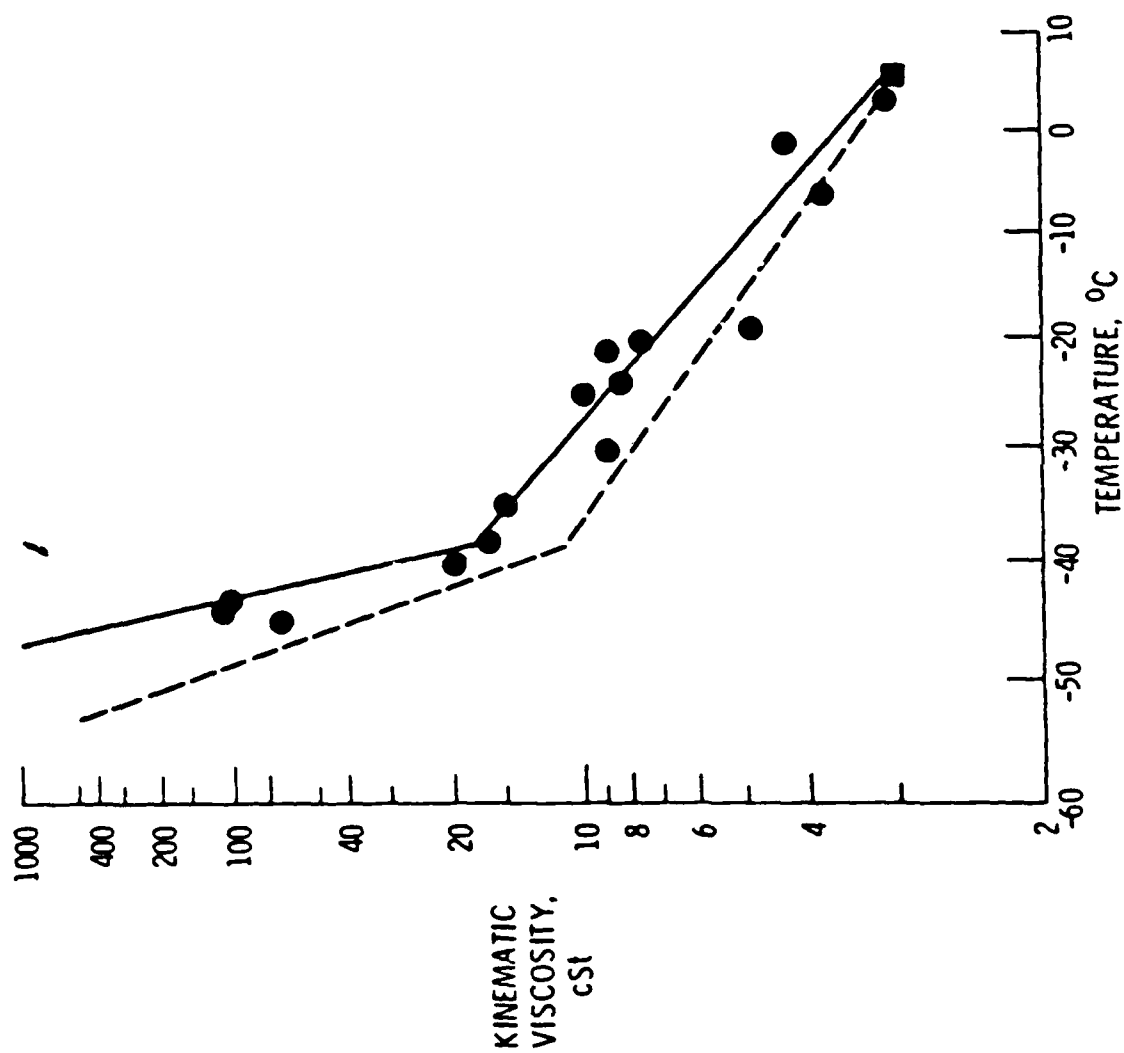


Figure 11. Viscosity data (—) and correlation (---) for fuel LFPA-4.

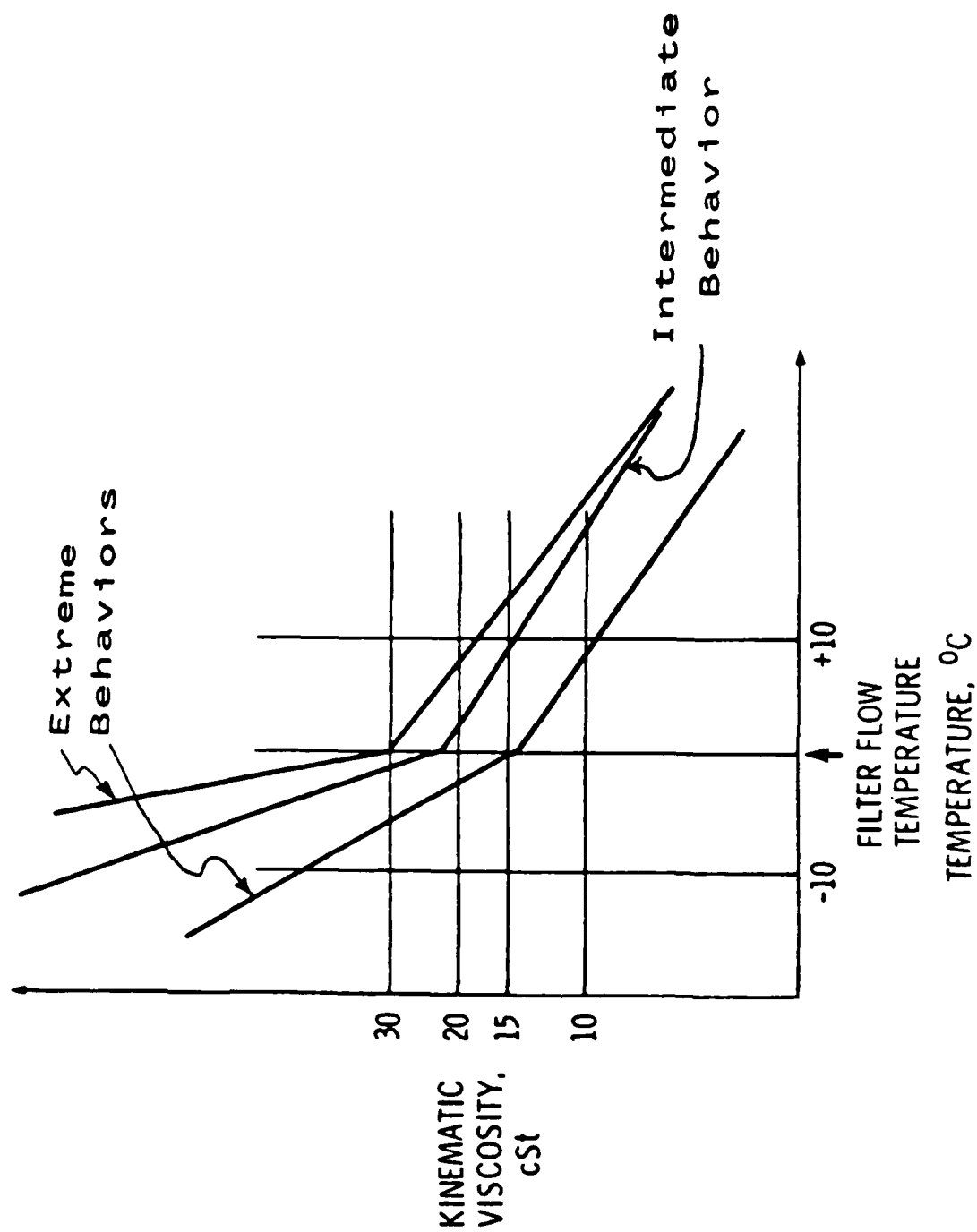


Figure 12. Characteristic behavior of test fuels.

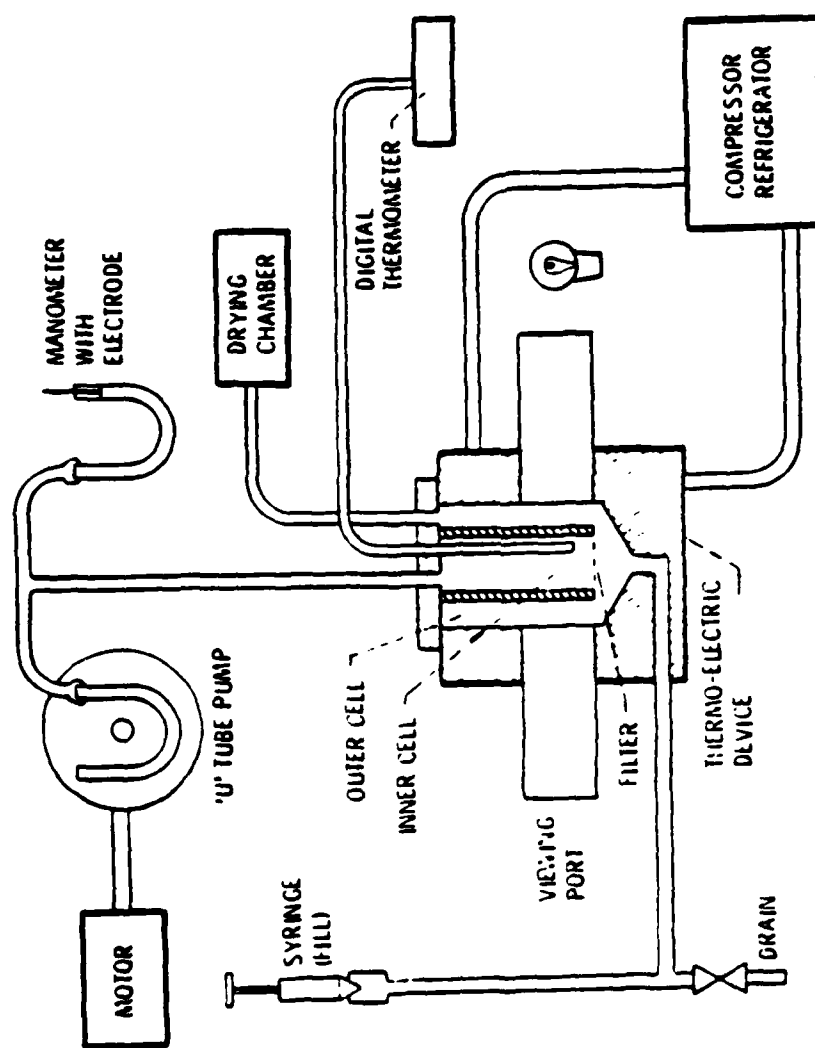
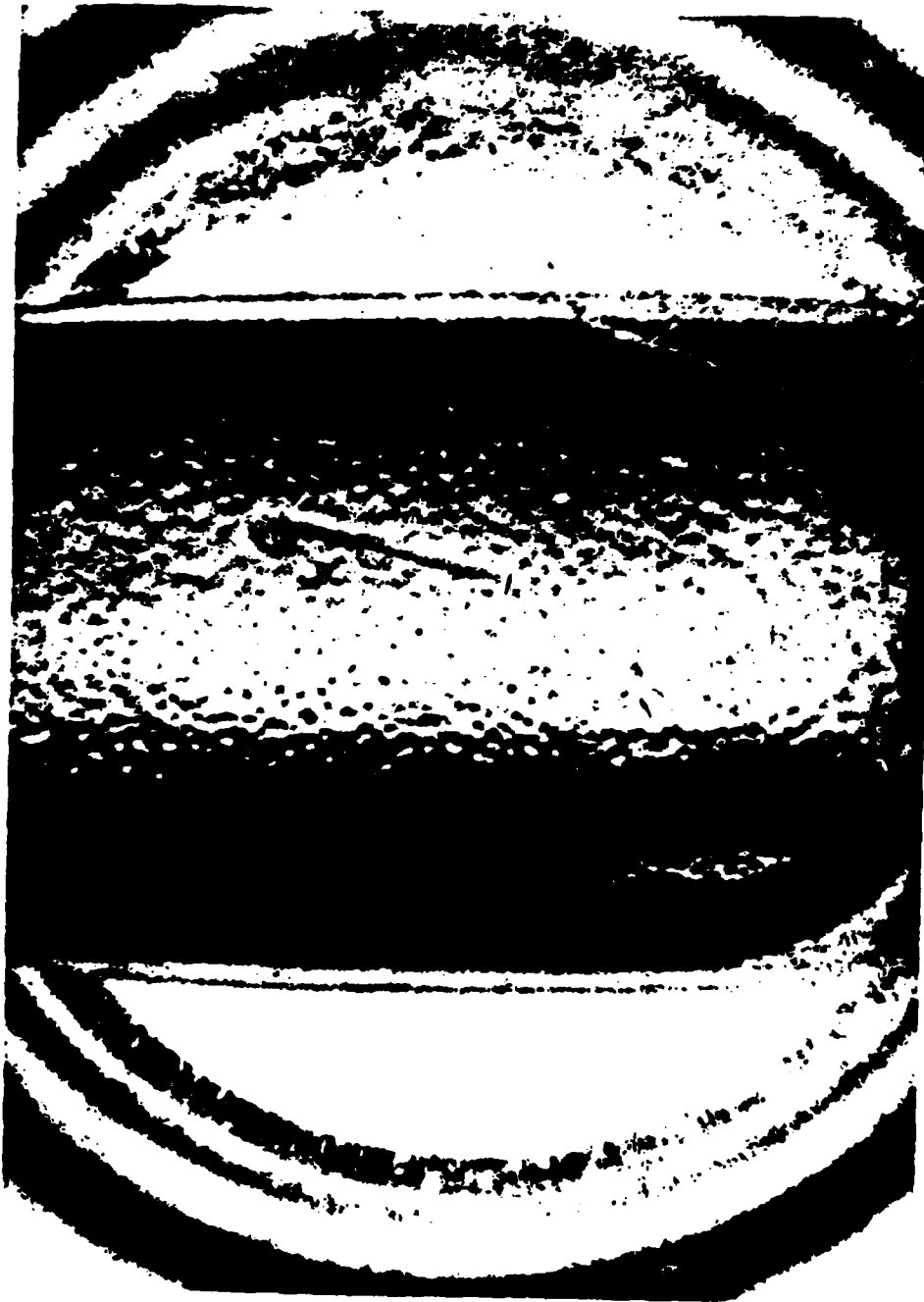


Figure 13. Illustration of the "seta-point" or filter flow apparatus.

Figure 14. View into the beta joint apparatus cold chamber.



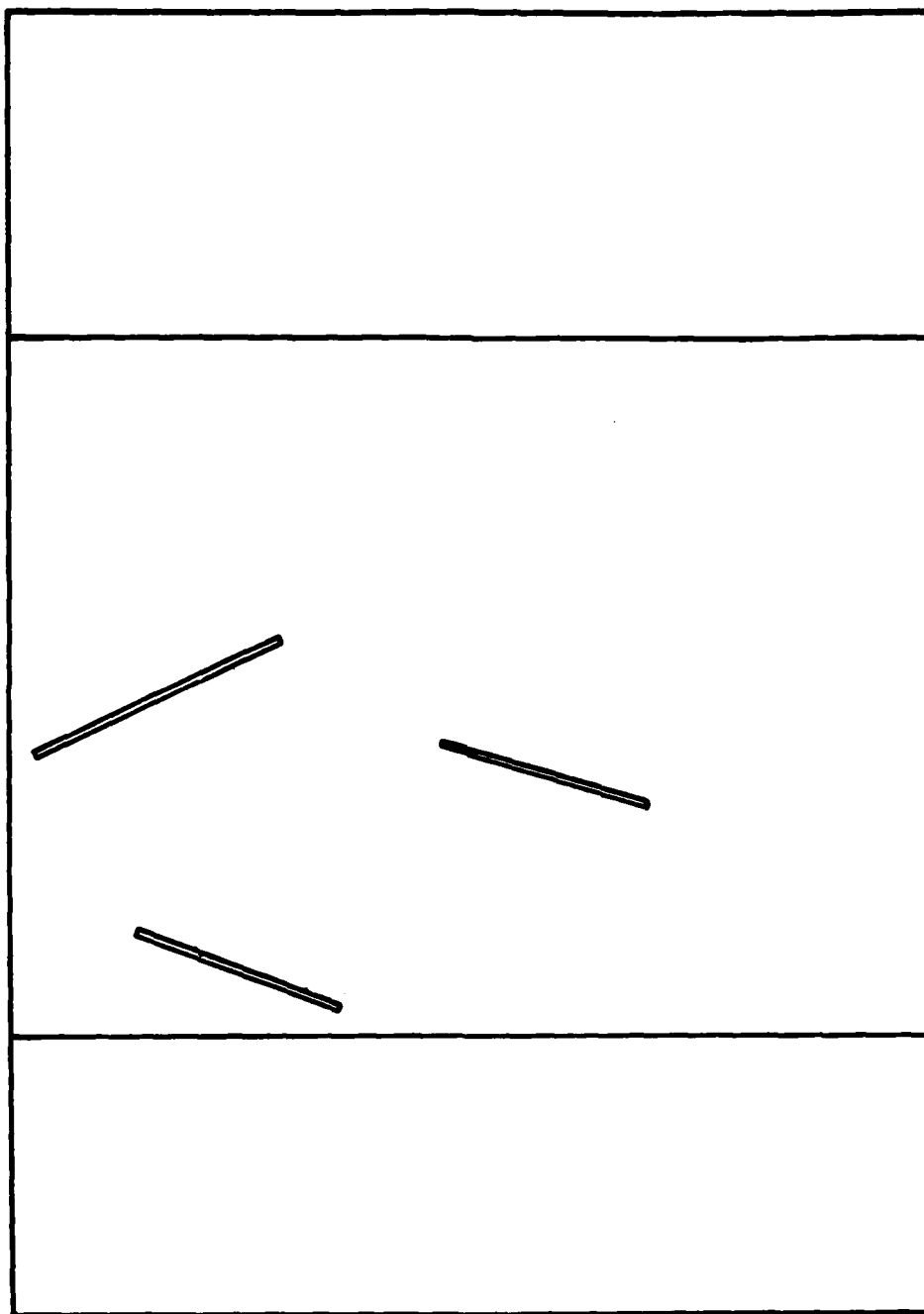


Figure 15: Line drawing to highlight Figure 14.

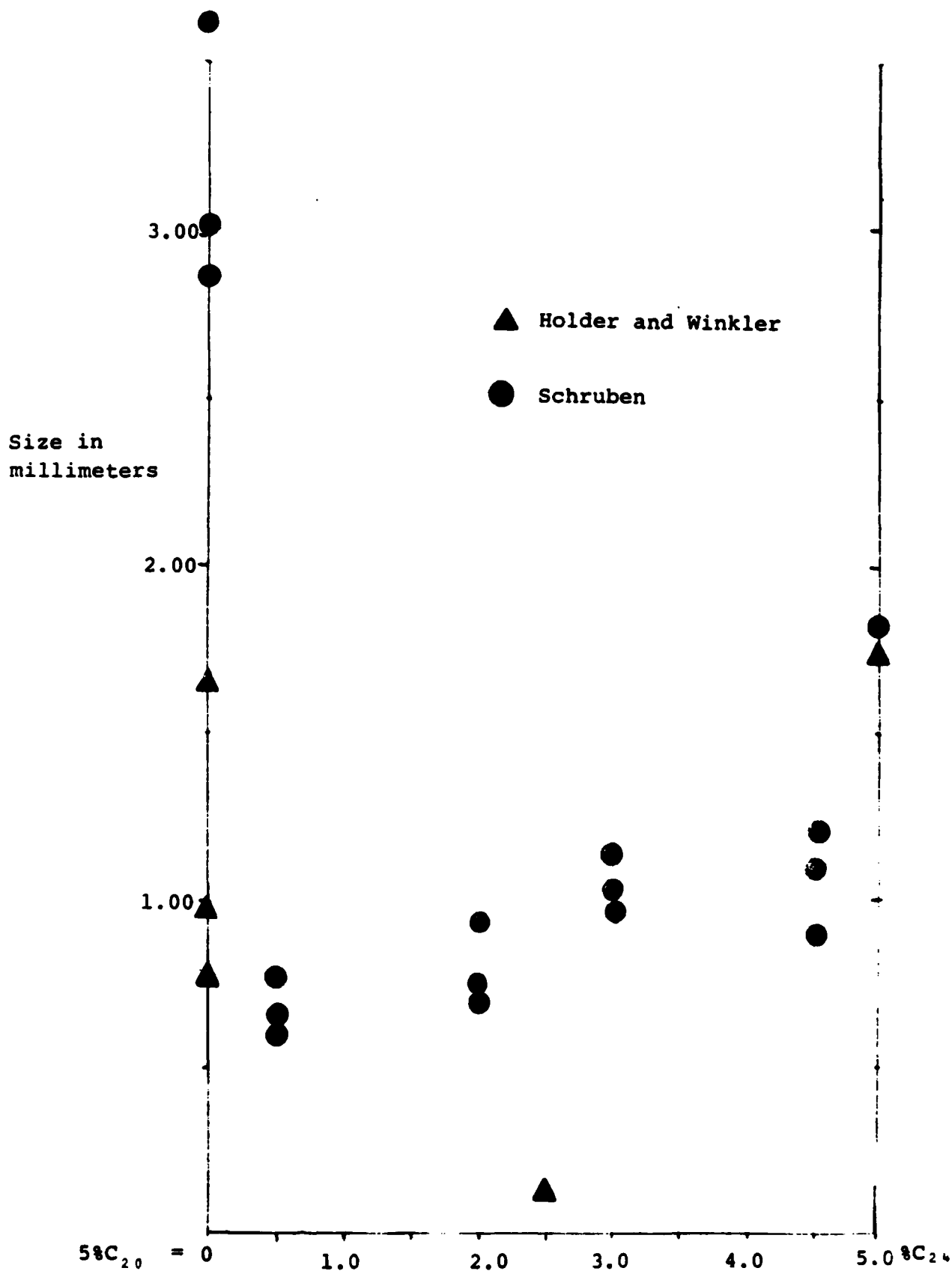


Figure 16. Size versus composition for the  $C_{20}/C_{24}$  system in Heptane. The sum of the  $C_{20}$  and  $C_{24}$  concentrations is 5 wt%.

## EXPERIMENTAL APPARATUS

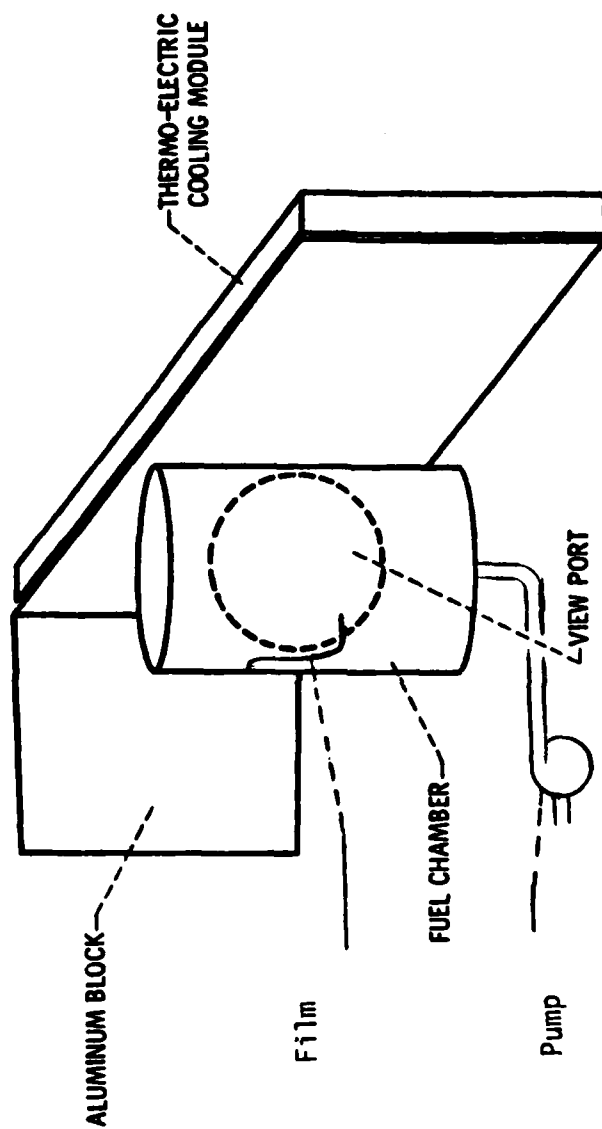


Figure 17. Cylindrical cavity with film forming on the sides.

# PROFILE OF SLUMPING WAX

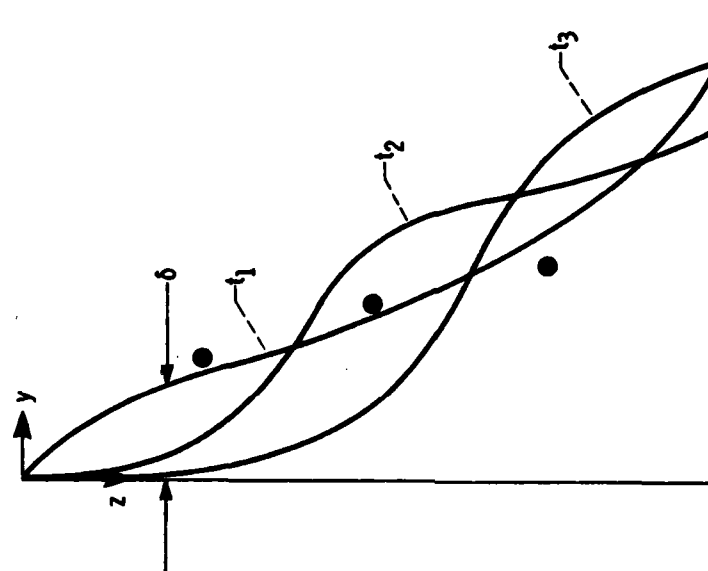


Figure 18. Composite of falling film profile over time.

# CLASSICAL FALLING FILM

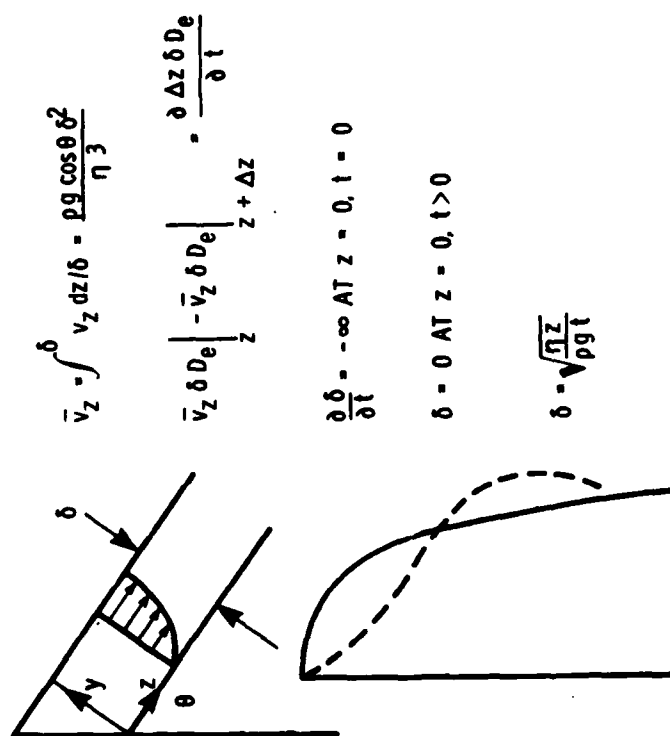


Figure 20. Development of falling film model.

MODIFICATIONS TO CLASSICAL FALLING FILM  
FORM SLUMPING WAX MODEL

$$\frac{\partial \delta}{\partial t} + \frac{\partial}{\partial z} \frac{(\delta \int \rho g \delta^2 [y/\delta - 1/2 y/\delta^2] dy)}{\eta_0 (1 + K_2 (\delta - y))} = 0$$

$$\frac{1}{1 + K_2 (\delta - y)} \sim 1 - K_2 (\delta - y)$$

$$\frac{\partial \delta}{\partial t} + \frac{\rho g}{\eta_0} \delta^2 \frac{\partial \delta}{\partial z} - \frac{K_2}{\eta_0^2} \rho g \delta^3 \frac{\partial \delta}{\partial z} = 0$$

$$z = z' \eta_0 / \rho g, K_3 = K_2 / 2$$

$$\frac{\partial \delta}{\partial t} + \delta^2 \frac{\partial \delta}{\partial z} - K_3 \delta^3 \frac{\partial \delta}{\partial z} = 0$$

Figure 19. Classical falling film model with linear viscosity variation across film.

## AUTOMATIC FUEL JETISON SYSTEM

Professor A. D. Krisch  
University of Michigan  
Ann Arbor, Michigan

I am going to talk about the automatic fuel jetison system, and I should start out by saying that I am most certainly not experienced in aircraft safety, but I have had experience with technology by working with experiments in electronics, various high-pressure mechanical systems, vacuum systems, and cryogenics systems. Some of that suggested these ideas:

My basic assumption is that, as I am sure all of you would agree, a significant fraction of crash-deaths are caused by fuel fires. So, one partial solution to this problem seemed to be to try to get the aviation fuel, in the event of a non-normal landing, as far away from the passengers as possible, as fast as possible, and as automatically as possible, because at the time of crash the pilot and the rest of the flight crew might not be in good shape to activate things. So the basic plan here is to have an automatic system to rapidly jetison the fuel upon aircraft impact as determined by the high-G reading on an accelerometer. I think an accelerometer is a device fairly familiar to all of you--they are in the seatbelts in your car to activate the seatbelts.

The jetison system, I would say could be activated in either of two ways, the primary way would be this accelerometer which is preset to trigger at something like 10 to 20 G's. I am not an expert, but I would assume that 10 to 20 G's would be a highly non-normal landing and that you would have a problem at that point. It could also be triggered manually if the pilot saw there was a very serious problem and he wanted to dump the fuel.

The second major element is that the fuel be driven out of the fuel tanks by some inert gas such as helium, argon, or nitrogen. Nitrogen, of course, is extremely cheap. You would have this under extremely high pressure. It would seem to me that the best way to do this is to jetison the fuel from orifices which were at the wing tank to get it as far away from the passengers as possible. Each jetison system would contain two electrically activated valves. One valve would connect the high-pressure gas tank to the fuel tank and the second valve would connect the fuel tank to the wing-tip. If you want to avoid an accidental jetison because some of the things have missfired, you could have two independant sets of valves in series. On the other hand, you might want to avoid no-jetison because one of the valves fail, so you might want to have two sets in parallel. How much you would want to do on this clearly depends on some studies about the failure probabilities of the valves, but these are various possibilities .

The third element is you might want to have an extra valve , again triggered by this automatic system which jams closed the lines from the tanks to the engines so that in the event of a non-normal landing, the fuel is cut off from the engines.

There are various types of accelerometer. The ones used in car seatbelts are ones that just swing back and forth, you may have noticed that when you hit your brakes they are triggered. I tend to think in an airplane you would want a spring-operated accelerometer because you wouldn't want the thing going off if the plane turned or something. I think they're rather routine devices.

A few problems and factors associated with this include the possibility the jetison system might be triggered accidentally in flight. One could have either a manual or automatic override so that the system would be disabled except perhaps within one minute of takeoff and landing. I think that would minimize the probability of this occurring.

The second problem is that the fuel jetison system might be triggered by noncrash bumps during takeoff or landing, but I guess we could solve that by setting the accelerometer at a sufficiently high level -- 10 to 20 G's is high enough that the bump must be fairly serious.

A third problem which is very real is that the fuel jetison system will increase the weight and thus the operating cost of the aircraft. And I think the high-pressure inert gas tank will be the heaviest component of the whole system. The tanks we buy our gas in are just cheap steel tanks that only cost 60 bucks, but they do weigh about 200 pounds. You would clearly want to do something better than that by building them out of high strength materials. I think if you use strapping like I have shown, it gives you a very good strength-over-weight ratio.

Another problem I have thought is a calculation that could be done. One should calculate what the jetison rate should be in gallons per second. For example with 2000 psi of gas, and one cm tubes and valves (you actually might want to consider two or three cm tubes and valves).

The big problem is that there might be a fire at the wing-tips. There are lots of things happening, maybe the wings will spring, and this does happen, but the people density is lower there so the event of a fire is much less serious than in the cabin.

That basically is the entire idea. I have not done any experimental work with this idea. Thank you.

#### WORKING GROUP MEETINGS

Chairmen: Working Group I - Mr. Chris Fuller  
Working Group II - Mr. Ed Wood  
Working Group III - Mr. Dick Tobiason

## WORKING GROUP GUIDELINES

Thursday, October 31, 1985 1045-1715

### A. Procedures

- Three parallel sessions (Brice, Ziegfield, Diamond Jim Room)
- Randomly selected participants from speakers
- Vu-graph material available for report out purposes
- Carnell, Brice Room
- Tobiason, Ziegfield Room
- Wood, Diamond Jim Room
- Open/Free communication with little input from FAA personnel - except information source.
- FAA personnel to float between groups, to see if assistance is required.

**Note:** All three topics (reduction of flammability, reduce fuel spillage, isolate fire) will be covered by each working group.

### B. Conduct of Session

- Questions and Answers to stimulate ideas and get participation.
- Inform Schroeder if you would like "closed" sessions (non-FAA attendees).
- If required notify Schroeder if further clarification from a speaker is required.

### C. Outcome of Working Group

- Prepare briefings for Friday, November 1 session starting at 0800 (at least 20 minutes but not to exceed 1 hour each).
- Content of Report
  - comments on what was contained in the presentations (both positive and negative).
  - list of research and development initiatives in each of the following categories which will mitigate post-crash fuel fire fatalities.
    1. Reduction of Flammability
    2. Reduce Fuel Spillage
    3. Isolate Fire
- prioritize initiatives in each category
- timing
  - 0-5 years      near term
  - 5-10 years     mid term
  - 10 years plus long term

## RECOMMENDATIONS OF WORKING GROUP I

### I. LONG-TERM GOALS

Cost/benefit studies should be broadened to include all injuries and deaths resulting from aircraft fuel fires, including in-flight fires, with costs reflecting all ground equipment and aircraft equipment required to implement a specific design change.

### II. SHORT-TERM GOALS

#### A. Top Priority

1. A government/industry technical group funded by the Federal Government should be established to review the results of the AMK program to determine any additional programs which should be pursued, and establish a priority for future FAA activities in this field. If a point is reached where it is determined that the technology does not exist to support this program, it will be terminated. This group should be composed of those of the highest technical capability in all pertinent areas of representation and should be appointed by a sufficiently elevated government level to provide them the authority necessary for carrying out their task.
2. Fuel spillage reduction: The FAA should explore the availability of current technology in the area of fuel bladder cells which would withstand a survivable transport aircraft crash scenario.
3. Isolation of fire: FAA should consider practical methods of fire-hardening the fuselage exterior surface.

#### B. Ancillary Recommendations

1. The FAA should, in conjunction with cabin total flood fire-fighting systems, improve occupant protective breathing hoods.
2. There should be a continued effort to emphasize design features to minimize the penetration of fuel tanks and/or cabin interior by failing structural components during a survivable crash condition.
3. The FAA should review all presentations which were made, regarding improved fire protection, during the private/industry session of this workshop.

4. Consideration should be given to the requirement of a tallmounted video camera with a cockpit display to provide the flight crew with an overall view which would reflect the status of the aircraft.

### III. GROUP CONSENSUS

Explosive suppressant capabilities of reticulated foam and metal mesh foils are recognized and accepted, however fuel must be contained for effectiveness.

## RECOMMENDATIONS OF WORKING GROUP 2

### I. R & D INITIATIVES

- A. Pursue realistic, large-scale flammability tests including powerplant involvement, and other combustible fluids.
  - 1. Define full scale tests.
  - 2. Develop meaningful small scale tests for additives.
- B. Evaluate alternative additives to FM-9.
- C. Explore new technology in fuel containment.
- D. Conduct additional low temperature blending tests for AMK, including degradability tests.
- E. Continue to define the AMK safety envelope.
- F. Continue aircraft operability study of AMK, both hardware and chemical.
- G. Pursue research in the area of gelatin additives, including synergistic effects.
- H. Explore physical and chemical kinetic studies.
- I. Explore fuel system arrangement and crashworthiness technology.
- J. Develop criteria to serve as a basis for regulatory efforts in the helicopter crashworthiness area.
- K. Conduct a more definitive analysis of CID and other accidents.

### II. LONG-TERM INITIATIVES

Develop an AMK that can be blended at the fuel depot.

## RECOMMENDATIONS OF WORKING GROUP 3

### I. DISCUSSION

- A. FAA should issue an RFP to determine if cost-effective additives are, or can be available.
  - 1. Performance specifications.
  - 2. Equipment constraints.
  - 3. Operating limitations.
  - 4. Incremental cost.
  - 5. No-blenders/degraders, it has to be indistinguishable from Jet A.
  
- B. AMK Issue:
  - 1. "Fine" droplet presence and role in supporting fire during large dump.
  - 2. Flame anchoring phenomena bluff body.
  - 3. Aircraft design considerations.
    - a. Fuel tanks are complex.
    - b. Fuel is transferred during flight.
    - c. Fuel tanks have limited pressure capability.
    - d. Crew action is limited.
    - e. Concepts should be "retrofitable" to existing aircraft.
    - f. Emission standards.
    - g. Recertification costs are "everything".
  
- C. Aircraft Operational Requirements
  - 1. Safe routing operations as in Jet A.
  - 2. Blending and introduction reliable.
  - 3. Quality control means and confidence.
  - 4. Universal application, worldwide.

5. Procedures/training.
6. Compatibility with fuel specs/other additives other fuels.
7. Fuel storage in a/c.
8. Defueling to Jet A tanker.
9. Equilibration time.
10. Cold weather and water.
11. Misfueling.
12. Bacteria protection.
13. Crew action.
14. Maintenance = low cost.

D. Can AMK do the job safely and reliably?

1. Need answers on long-term operating conditions.
2. R & M data?
3. Failure modes?

E. Conclusions

1. AMK, or any fuels modifier, shall not degrade safety.
2. Contribution to safety via AMK is unknown.
3. Other safety actions contribute to post crash fire reduction: prevention and design.
4. Insufficient FAA evaluation of alternative AMK additives.
5. Cooperative work should get "final" answers to allow final decision.
6. Incremental benefits will be costly, and not in the near term.

## II. RECOMMENDATIONS TO FAA

### A. General

1. Maintain a program with industry in modified fuels, including AMK, not to exceed 3 years (EOY 1988).
2. Develop AMK into a reliable, operational, cost-beneficial and safe fuel.
3. Update cost/benefit analysis.
4. Reinstate "SAFER" type advisory group for fuel safety.
5. Develop plan for industry peer review within 6 months.

### B. Specific

1. Determine operating envelope of AMK fuels, including methodology criteria.
2. Determine potential risk reduction (accident data).
3. Develop complete validated technical "package" prior to rulemaking if NPRM is FAA intent.
4. Develop reliable QC measures useful in the field.
5. Develop a flight program to assess long-term, operational effects.
6. Encourage new ideas.

### C. Fuel Spillage

1. Foams, explosives, gels, and bladders.
2. SAFER recommended AMK.
3. No new proposals.
4. Current bladders meet FAA crash requirements.

## SUMMARY OF WORKING GROUPS

Although separate topics had originally been planned for each of the workshops, it was decided to split the total attendance into three groups and have them independently address the needed research for all fuel safety issues. The most encouraging aspect of the workshops was the fact that although each group considered their subjects independently, almost identical content resulted. All recommended the continuation of some form of safety fuel research. There was a strong feeling that FM-9 AMK per se was too narrow an approach and that future research should be expanded to take advantage of possible synergistic effects of other additives.

Recommendations of the working groups are summarized into six categories as follows:

### FM-9 EFFORT CONTINUATION

- o Perform Definite Analysis of CID and Other Accidents
- o Bluff-Body Flame Anchoring
- o Presence/Effect of "Fines"
- o Low-Temperature Blending Tests
- o Degradability Tests
- o Physical and Chemical Kinetic Studies

### ANTI-MISTING FUEL RESEARCH (ALTERNATIVES TO FM-9)

- o Define Envelope
  - Operational Environment/Requirements
  - Risk Reduction
  - Reliability and Maintainability
  - Quality Assurance
  - Failure Modes
  - Aircraft Design Considerations
  - Depot Blending
  - Aircraft Operability Study
  - Auxiliary Hardware
- o Define and Pursue Small-Scale Tests

- o Define and Pursue Large-Scale Tests
- o Define and Pursue Engine/Flight Program

#### **CONTAINMENT**

- o Assess Current Technology - Bladder Cells
- o Fire Harden Fuselage Exterior
- o Minimize Fuel Tank Penetration
- o Regulatory Requirements for Helicopter Crashworthiness

#### **POST-CRASH FIRE SUPPRESSANTS**

- o Research into Current Technology of
  - Microencapsulation
  - Gelation
  - Reticulated Foam
  - Metal Mesh Foils
  - Other Additives
- o Total Flood of Interior Aircraft with Passenger Protective Hoods

#### **ANALYSES**

- o Update Cost/Benefit FM-9
- o Define Scope of Problem That Could Be Solved

#### **OTHER**

- o Establish Technical Advisory Group
  - ALA "SAFER"
  - High Level, Highly Technical
  - Review and Report Periodically on FAA Program/Progress
- o Install Tail-Mounted Video Camera With Cockpit Display
- o Industry Review of Plan in Six (6) Months

## APPENDIX A

### BIOGRAPHICAL SKETCHES OF PRESENTORS

#### 1. WILLIAM W. BANNISTER

Dr. William Bannister is currently a Professor of Chemistry at the University of Lowell, Lowell, Massachusetts, and the President of the Aviation Fuel Safety Company in Chelmsford, Massachusetts. He holds a Bachelor of Science Degree in Chemistry and a Ph.D. in Chemistry from Purdue University.

Dr. Bannister was a professor at the University of Cincinnati and Tennessee Technical University prior to coming to the University of Lowell. He also worked as a staff chemist at Proctor and Gamble Company.

His areas of expertise include gelled fuel formulations, oil spill control and recovery, and organic reaction mechanisms. He is published in these subject areas. In his role as President of the Aviation Fuel Safety Company, Dr. Bannister is pursuing the development of a fire-safe aviation fuel.

#### 2. ROBERT GORDON BAYLESS

After receiving his Bachelor of Science Degree in Chemistry from Central State University in Wilberforce, Ohio, Mr. Bayless obtained his Master's Degree in Physical Chemistry from the University of Cincinnati. He spent nine years with National Cash Register Company (NCR) during which he perfected microencapsulation technology for the carbonless paper and time-release aspirin applications. When the carbonless paper area was sold, he was offered an opportunity to relocate with NCR to Appleton, Wisconsin. It was at this time that he decided to start his own company, with NCR's blessings, and to continue the efforts he had started. He has since spent an additional 13 years with CSI developing many new techniques. Out of this work has come such marketable products as a microencapsulated epoxy called CAPLOK, which is used on threaded fastener locking devices and a microencapsulated silicon oil lubricant named SILCAP. In addition, many other products are presently in various stages of development in the CSI lab.

### 3. STEVEN L. BAXTER

Dr. Baxter is currently the Supervisor of an Exploratory Research Group in the Specialty Products Research Section of Conoco's Chemicals Research Division. The responsibilities of his group include product development and exploratory polymer research in drag reduction, oil field chemicals, and antimisting jet fuel. Dr. Baxter received a Ph.D. in Organic Chemistry from Brigham Young University in 1981 and has worked in the Chemicals Research Division of Conoco from 1980 to the present.

### 4. NEAL A. BLAKE

Mr. Blake's service with the Federal Aviation Administration began in 1962 as a member of the Systems Design Team, Systems Research and Development Service. He served as Technical Assistant to the Air Traffic Control Development Division from 1966 to 1972. He became Technical Advisor in 1972 to the Director, Office of Systems Engineering Management. Mr. Blake was promoted to Deputy Associate Administrator for Engineering. From 1952 to 1962, he served in progressively responsible research and engineering positions with the Capehart Farnsworth Corporation (Division of ITT) and was Associate Lab Director of the Avionics Transmission Lab at ITT's New Jersey facility. He has an airline transport pilot's certificate, with multi-engine and type ratings.

Mr. Blake attended Yale University and graduated in 1952 with a B.S. and M.S. Degree in Electrical Engineering.

### 5. HOMER W. CARHART

Dr. Carhart received his Ph.D. in Organic Chemistry from the University of Maryland. After serving two years as Professor of Chemistry at Gallaudet College for the deaf, he joined the Naval Research Laboratory as a Research Chemist where in 1952 he became Head of the Fuels Branch. He currently heads a large research team working on combustion, fire protection, fuels, and Chemical/Biological defense. Relevant to this Workshop he has published in the areas of flammability, fuel properties as related to safety, anti-misting, fire behavior, and fire protection for Navy platforms - aircraft, ships and submarines. He was Chairman of the Coordinating Research Council's Task Force on Aviation Fuel Safety, Chairman of the International Academy of Sciences and is currently Chairman of the Council's Committee on Evaluation of Industrial Hazards. He was a consultant to the Board and member of the Fire Panel in the investigation of the fatal Apollo space capsule fire. He is the recipient of the Naval Research Laboratory's E.O. Hulburt Award and of the Navy's highest award to a civilian, the Distinguished Civilian Service Award.

## 6. JOHN H. ENDERS

John H. Enders is a graduate mechanical engineer, with a degree from the Case Institute of Technology; he has worked in aerospace research and engineering activities for most of his professional career.

He began his career as a Research Staff Member of the National Advisory Committee for Aeronautics (NACA), the predecessor of the National Aeronautics and Space Administration (NASA), conducting rocket engine research. He also served for four and one-half years as a Pilot and Development Engineer with the United States Air Force. After his Air Force service, Mr. Enders rejoined the staff of NASA's Lewis (Ohio) Research Center as a Research Test Pilot, where he conducted several projects, including zero gravity test flights.

In 1962, he transferred to NASA headquarters in Washington, D.C., served as Technical Assistant to the NASA Administrator and as Manager of Aircraft Safety and Operating Problems Research until 1979, when he became an independent Consulting Engineer. He became President of the Flight Safety Foundation in April 1980 and continues to hold that position.

From 1969-1971, Mr. Enders served as NASA liaison member on the staff of the National Aeronautics and Space Council. He was Technical Advisor to the Federal Aviation Administration's (FAA) Associate Administrator for Aviation Safety from 1976-1977.

Mr. Enders served as Chairman of FAA's Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, and was a member of the National Research Council's Ad Hoc Committee on Aircrew-Vehicle System Interaction.

7. **BRUCE C. FENTON**

Mr. Fenton graduated from Tennessee Tech in August, 1966 with a B.S. degree in Mechanical Engineering. Until June, 1980, Mr. Fenton was employed as an Aerospace Engineer with the Naval Air Propulsion Technology and Project Engineering Department with project engineering responsibilities for numerous engine development and qualification programs. From September 1975 to October 1976, he participated in NAPC's management training program as the Assistant to the Plans and Programs Officer in the Resource Management Department. In July 1980, Mr. Fenton accepted an Aerospace Engineer position at the Federal Aviation Administration (FAA) Technical Center at the Atlantic City Airport, New Jersey, in the Aircraft and Airport Systems Technology Division. As a Senior Engineer in the Engine/Fuel Safety Branch, he has served as Project Manager and Contracting Officer Technical Representative in support of the overall Anti-misting Kerosene (AMK) Fuel Program. His primary responsibilities in the AMK program are in the compatibility, production, large-scale evaluation, and full-scale validation cases. The AMK full-scale validation phase includes the joint FAA/National Aeronautics and Space Administration Full-scale Transport Controlled Impact Demonstration Program.

8. **CHRIS FULLER**

Mr. Chris Fuller has served nine years as Chief of System Safety, Sikorsky Aircraft Division of United Technologies. While in this position he has been involved in the Blackhawk, X-Wing, and LHX programs. Mr. Fuller also has twenty years experience in Aviation Safety with the United States Army. He has accumulated 3500 hours as a Helicopter and Fixed Wing Pilot. He has investigated more than 150 helicopter and fixed wing accidents. Mr. Fuller holds a Master's Degree in Aerospace Systems from the University of Southern California.

9. **EUGENE KLUEG**

Mr. Eugene Klueg has 28 years experience with the Civil Aeronautics Administration and the Federal Aviation Administration in aircraft safety research and development. A Program Manager since June 1974, he is responsible for the supervision, management, and control of Technical Center projects relative to antimisting fuel and aircraft air pollution. His prior experience includes program responsibilities for aircraft propulsion system safety, airframe crash fire hazards, in-flight fire safety, and engine exhaust emissions. He has managed or served as project engineer on projects associated with fuel tank explosions, fuel tank inerting, runway slush, aircraft safety test facilities design, impact-resistant windshields, and helicopter crash-resistant fuel systems. Mr. Klueg holds the degree of Bachelor of Aeronautical Engineering from the University of Detroit. He currently holds the position of Supervisor Aerospace Engineer in the Aerospace Systems Technology Division at the FAA Technical Center.

**10. DR. A.D. KRISCH**

Dr. Krisch serves as Professor of Physics at the University of Michigan, Ann Arbor, Michigan.

Dr. Krisch conducts experiments involving high energy nuclear physics. He performs this work utilizing the 30 billion Electron Volt AGS Accelerator at the Brookhaven National Laboratory on Long Island, New York.

**11. HONORABLE NORMAN Y. MINETA**

Norman Y. Mineta represents California's 13th Congressional District, which includes portions of San Jose, the cities of Campbell, Los Gatos and Santa Clara, as well as unincorporated parts of Santa Clara County.

Congressman Mineta earned a Bachelor of Science Degree in Business at the University of California at Berkeley in 1953. He served as a military intelligence officer during tours of duty in Japan and Korea. Returning to San Jose, he worked with his father in the family insurance business. After serving in various political posts from 1962, Congressman Mineta was elected as Mayor of San Jose in 1971, thus becoming the first Japanese-American mayor of a major U.S. city. In 1974, he won a seat in the U.S. Civil Service Committee and the Public Works and Transportation Committee. In the 95th Congress, he chaired the Public Buildings and Grounds Subcommittee. In the 96th Congress, he was elected chair of the Subcommittee on Investigations and Oversight and Chair of the Task Force on the Budget Process.

Congressman Mineta chaired the Subcommittee on Aviation in the 97th Congress. In addition to membership on various other House Committees, he retained this chairmanship throughout the 98th congressional session and continues to promote aviation safety while holding the position in the 99th congress.

**12. LAWRENCE M. NERI**

Mr. Neri presently serves as Program Manager in the Crashworthiness/Structural Airworthiness Branch responsible for both fixed and rotary wing aircraft safety programs. He came to the Federal Aviation Administration Technical Center in 1968 after receiving a Bachelor's Degree in Mechanical Engineering from Villanova University.

Prior to his assignment to the Crashworthiness Branch, Mr. Neri was associated with efforts which investigated advanced concepts in aircraft fire propulsion and fire safety protection.

Mr. Neri holds a Master's Degree in Environmental Studies (life science) and has authored or co-authored over 14 formal technical reports as well as numerous letter/data reports. He is a member of the American Society of Mechanical Engineers and the Institute of Environmental Science.

**13. DR. PRADIP PARIKH**

Dr. Pradip Parikh received his Ph.D. in Aerospace/Mechanical Engineering from Stanford University in 1977. He was an Acting Assistant Professor/Research Associate in the Mechanical Engineering Department at Stanford from 1977 to 1981. He joined JPL in November 1981 as a member of the technical staff and has been involved in various aspects of the AMK program including flammability, blending, low temperature performance, and degradation.

**14. TOM PEACOCK**

Tom Peacock earned a Bachelor of Science Degree in Physics from Ohio State University. He is a Senior Staff Engineer in the Propulsion and Environmental Control Systems Engineering Staff Group at Douglas Aircraft, where he is responsible for fuels, fuel systems, and fire protection. He is an FAA designated engineering representative in these areas. Mr. Peacock has been active for over twenty years in industry activities on fuel fire safety, including the SAFER Committee and the Coordinating Research Council's Fuel Systems Safety Committee. He is currently the Chairman of ASTM Technical Sub-Committee D2-J on aviation fuels.

**15. CHARLES G. RIVERS**

Charles G. Rivers, Jr. is an AMK Technical Manager in the Corporated Resources Department of ICI Americas, Inc. Mr. Rivers joined the company in 1961 as a Chemical Engineer. He has worked in production, process design, and program technical management, holding several key positions since that time.

A native of Greenfield, Massachusetts, Mr. Rivers received his Bachelor of Science Degree in 1961 from Massachusetts Institute of Technology and Master's Degree in Chemical Engineering from the University of Delaware.

**16. DR. V. SAROHIA**

Dr. V. Sarohia received his Master's and Ph.D. Degrees in Aeronautics from California Institute of Technology (CalTech) in 1971 and 1975 respectively. He joined the Caltech Jet Propulsion Laboratory in May 1975, where he is currently the Technical Group Supervisor of the Fluid Dynamics Group. Presently, he is the Task Manager of the JPL Antimisting Kerosene Program, sponsored by DOT/FAA Technical Center Atlantic City, New Jersey. He is also author/co-author of over 40 technical papers/reports in the areas of acoustics, shock dynamics, combustion, turbulent shear flows, and many aspects of anti-misting fuels technology such as fuel breakup, flame propagation, blending, compatibility, skin friction, and heat transfer studies, etc.

**17. FORREST W. SCHAEKEL**

Mr. Forrest W. (Skip) Schaeckel is a Supervisory Chemist and Chief of the Fuels and Lubricants Branch in the Belvoir Research and Development Center at Fort Belvoir, Virginia. He is actively engaged in the Army Fire-Resistant Fuel Program and has been involved in this effort for the past 16 years. He has co-authored several technical reports on Fire-Resistant Fuel with personnel of the Belvoir Fuels and Lubricants Research Facility at Southwest Research Institute in San Antonio, Texas. These reports covered several types of fuels designed to reduce the fire threat in Army Material and related to the formulation and preparation of the fuels, the determination of physical and chemical properties, and the performance of fire-resistant fuels in military engines and when subjected to ballistic impact and/or accidental fires in combat equipment.

Mr. Schaeckel has a Master of Science Degree (Chemistry) from the University of Toledo (Ohio) and has taken advanced training at Michigan State University and Several Army training activities.

18. DONALD A. SCHROEDER

Mr. Schroeder's service with the Federal Aviation Administration began in 1958 as a Field Engineer responsible for construction of air navigation facilities within the Eastern Region. After six years in the New England Area Office in positions of Engineering, Maintenance and Program Planning and Budgeting, Mr. Schroeder was transferred to Washington Headquarters in the Systems Maintenance Service. In 1969, he was selected as one of the six participants in the Air Transportation System Specialist Program and received his Master of Engineering (Transportation) Degree at the University of California-Berkeley.

Following this program, Mr. Schroeder worked in the National Airspace System Program Office and the Office of Policy and Plans. He was promoted in 1974 to a management position in the Office of Plans, supervising the Airport's Policy and Criteria Branch. In 1975, he was selected for the DOT's Executive Development Program and was detailed to the Western and Southern regions as Special Assistant to the Regional Director. Following a nine-month assignment as an Aviation Economic Policy Analyst in the Office of the Secretary, Mr. Schroeder held a series of management positions in the Office of Labor Relations, Flight Standards Service and Airway Facilities Service. He assumed the duties of his present position in December, 1982. Mr. Schroeder received his Bachelor of Science Degree in Civil Engineering in 1958 from Syracuse University.

19. DR. DALE L. SCHRUBEN

Dr. Dale Schruben is currently an Assistant Professor in the Department of Chemical Engineering at the University of Akron, Ohio. Prior to this position, he was associated with Exxon Research and Engineering from 1978-1982 as an engineer, performing research analysis of Fleet test data, synfuels, gasoline and diesel fuel compatibility with polymers. Dr. Schruben spent 1968-197 with Westinghouse Electric Corporation, serving as Senior Engineer involved with nuclear core flux and power computation, and processing powdered nuclear fuel. During this time, he was also a teaching assistant at Carnegie-Mellon University.

Dr. Schruben holds a Bachelor of Science Degree in Physics and Nuclear Engineering from Kansas State University, a Master of Science Degree in Chemical Engineering from the University of Minnesota, and a Ph.D. in Chemical Engineering from Carnegie-Mellon University. He has published numerous reports and papers on petroleum product quality and rheology, crystallization, fluid mechanics and field dependent transport properties.

20. BRUCE M. SINGER

Bruce M. Singer is the Manager of the Aircraft and Airport Systems Technology Division at the Federal Aviation Administration (FAA) Technical Center. In his current position, Mr. Singer is responsible for the planning and conduct of research, development, test, evaluation and demonstration programs in the areas of airport technology, engine and fuel safety, crashworthiness and structural airworthiness, flight safety, fire safety, and aviation security. He has been at the Technical Center since 1980, where he previously served as Assistant Chief of the Aircraft and Airport Systems Technology Division, after serving as a Technical Analyst with the Engineering Management staff.

Mr. Singer holds a Master of Science Degree in Transportation Planning from Polytechnic Institute of New York and a Bachelor of Science Degree in Civil Engineering from Manhattan College. He is a member of the American Society of Civil Engineers (ASCE), and a registered professional engineer in the State of New York.

21. HOWARD SKAVDAHL

Mr. Skavdahl, Chief of Propulsion Research and Engine Technology for the Boeing Commercial Airplane Company, received a Bachelor of Science Degree in Aeronautics from the University of Colorado, Boulder in 1948 and a Master of Science Degree from California Institute of Technology in 1951.

Mr. Skavdahl joined the engineering staff of the Rand Corporation, Santa Monica, California and the Boeing Commercial Airplane Company in 1961. He held various positions in Propulsion Research and Preliminary Design until 1970, when he became Technology Manager for the Augmentor Wing Jet STOL Research Airplane Program, funded by NASA and the Department of Trade and Industry of Canada. This was followed by the same assignment on another research airplane program, the QSRA (Quiet Short-Haul Research Airplane) for NASA.

Mr. Skavdahl has been in his current position since 1978. He has served on a number of Industry/Government committees including the FAA sponsored SAFER Committee and the AIA sponsored committee on Aircraft Engine Emissions and has co-authored several SAE and AIAA papers.

**22. DR. MARTIN SUMMERFIELD**

Dr. Summerfield is President of the Princeton Combustion Research Laboratories (PCRL) as well as a Professor Emeritus of Engineering at Princeton University. The company, PCRL, performs research and development of both an experimental and analytical nature, in combustion systems.

**23. MR. HORACE ALLEN TANSILL, SR.**

Mr. Tansill has over 50 years experience as a private pilot. His interest in fire prevention began when, at the age of five years, his family's home was destroyed by fire.

Mr. Tansill is now a private inventor/consultant in Santa Barbara, California, holding two patents on specialized foam products.

**24. ALLAN R. TOBIASON**

Mr. Tobiason joined Air Transport Association (ATA) as the Assistant Director of Engineering-Safety Technology in March 1985 with major responsibilities for the safety aspects of aircraft cabin interiors flammability and passenger seat strength. Prior to his current position, he was Program Manager of Aviation Safety Technology for the National Aeronautics and Space Administration (NASA) Headquarters. At NASA, he was responsible for AMK research which investigated AMK engine compatibility and the RPV aspect of the B-720 CID program. Mr. Tobiason participated in the SAFER activity which made recommendations to the Federal Aviation Administration (FAA) on post-crash fire safety (cabin materials and fuels).

His experience includes 20 years as Master Army Aviator with Bachelor and Master of Science Degrees in Civil Engineering, and he is a graduate of the U.S. Navy Test Pilot School. He managed the Army Cheyenne AH-56A flight test program at Lockheed and served as Aeronautics Assistant for the, Executive Office of the President of the United States. His operational flying includes tours in the United States, Europe, North Africa, Middle East, and Vietnam, where he flew 600 combat hours as a commander of a forward air control unit.

Upon completion of his military career in 1977, he joined the National Transportation Safety Board as an Aeronautical Engineer and performed analyses of flight and cockpit voice recorder information in support of 18 accident investigations. Following NTBS, he joined NASA, managing both aviation safety and experimental flight test programs for five years.

25. JERRY C. TRIPPE

Mr. Jerry C. Trippe is Executive Vice President and Co-Founder of General Technology Applications, Inc. He has played a key role in GTA's research in mist suppression additives and is a Co-inventor of a number of processes for manipulating high molecular weight polymers and other difficult to process materials.

26. DR. PETER WILFORD

Mr. Wilford holds a B.S. Degree in Chemistry and a Ph.D. in Physical Chemistry.

He has worked at the Royal Aircraft Installation for twenty years; his primary area of concern being fuel matters.

27. ED WOOD

Mr. Ed Wood holds an Aerospace Engineering Degree from the University of Maryland. After serving four years in the United States Air Force, he became a Flight Test Engineer for Boeing Commercial Airplane Company in Seattle, Washington. He was an Aeronautical Research Engineer for the United States Navy, and then an Aircraft Accident Investigator for CAB. Over a 16 year period, Mr. Wood has held various positions within the FAA, including that of Executive Director of the SAFER Committee. Since 1980, Mr. Wood has been the Director of Engineering for the Flight Safety Foundation.

28. ALAN ZENGEL

Alan Zengel is Manager at the Coordinating Research Council (CRC), an industry-sponsored organization responsible for cooperative research between the petroleum industry and the engine and airframe industries.

Mr. Zengel has worked with the CRC for 16 years and is employed by the Fuels and Lubricants Division of the Air Force Aeropropulsion Laboratory at Wright-Patterson prior to joining the CRC.

Mr. Zengel holds a Bachelor of Science Degree in Chemical Engineering from the University of Illinois and a Master of Science Degree in Chemical Engineering from Ohio State University.

ATTACHMENTS

## BIBLIOGRAPHY

REPORT NO.	AUTHOR	PERFORMING ORGANIZATION	TITLE	DATE
FAA-RD-76-109	S. ZINN, JR. T. EKLUND W. NEESE	FAA TECH CENTER	PHOTOGRAPHIC INVESTIGATION OF MODIFIED FUEL BREAKUP AND IGNITION	SEPTEMBER 1976
FAA-RD-77-10	R. MANNHEIMER	SMRI	RHEOLOGY STUDY OF ANTIMIST FUELS	JANUARY 1977
FAA-RD-77/13	R. AHLERS	FAA TECH CENTER	FULL-SCALE AIRCRAFT CRASH TEST OF MODIFIED JET FUEL	JULY 1977
FAA-RD-77-114	T. EKLUND	FAA TECH CENTER	EXPERIMENTAL SCALING OF MODIFIED FUEL BREAKUP	AUGUST 1977
FAA-RD-78-50	A. SAN MIGUEL M. WILLIAMS	NAVAL WEAPONS CENTER	ANTIMISTING FUEL SPILLAGE/AIR SHEAR TESTS AT NAVAL WEAPONS CENTER	MARCH 1978
FAA-RD-78-54	T. EKLUND W. NEESE	FAA TECH CENTER	DESIGN OF AN APPARATUS FOR TESTING THE FLAMMABILITY OF FUEL SPRAYS	MAY 1978
NA-78-66-LR	T. EKLUND J. COX	FAA TECH CENTER	FLAME PROPAGATION THROUGH SPRAYS OF ANTIMISTING FUELS	NOVEMBER 1978
FAA-RD-79-62	R. MANNHEIMER	SMRI	RESTORING ESSENTIAL FLOW AND IGNITOR PROPERTIES TO ANTIMISTING KEROSENE (AMK) FOR TURBINE AIRCRAFT OPERATIONS	FEBRUARY 1979
FAA-RD-79-52	R. PARDEE	LOCKHEED-GEORGIA CO.	AIRCRAFT FUEL SYSTEM SIMULATOR TESTS WITH ANTIMISTING KEROSENE (JET-A FUEL WITH FM-9 ADDITIVE)	MAY 1979
TR 183		NAVAL AIR ENGINEERING CENTER	FULL-SCALE AIRCRAFT CRASH TESTS OF ANTIMISTING KEROSENE	AUGUST 1980
CT-80-162		FAA TECH CENTER	ENGINEERING AND DEVELOPMENT PROGRAM PLAN ANTIMISTING FUEL (REVISED FEBRUARY 1983)	SEPTEMBER 1980
FAA-CT-81-156	E. KLUEG	FAA TECH CENTER	AIRCRAFT FIRE SAFETY RESEARCH WITH ANTIMISTING FUELS	NOVEMBER 1980
FAA-CT-81-11	R. SALMON	FAA TECH CENTER	WING SPILLAGE TESTS USING ANTIMISTING FUEL	FEBRUARY 1981
FAA-CT-81-51	J. TRIPPE P. WATERS A. HADENMANN	GENERAL TECHNOLOGY APPLICATIONS, INC.	APPLICATION OF GENERAL TECHNOLOGY APPLICATIONS, INCORPORATED (GTA) BLENDING PROCESS TO ANTIMISTING FUEL ADDITIVES	MAY 1981
FAA-CT-81-58	A. FIORENTINO R. DE SAVO T. FRANZ	PRATT & WHITNEY AIRCRAFT GROUP	AN ASSESSMENT OF THE USE OF ANTIMISTING FUEL IN TURBOPAN ENGINES	JUNE 1981
FAA-CT-81-153	R. MANNHEIMER	SMRI	DEGRADATION AND CHARACTERIZATION OF ANTIMISTING KEROSENE (AMK)	JUNE 1981
FAA-CT-81-181		FAA TECH CENTER	AIRCRAFT RESEARCH AND TECHNOLOGY FOR ANTIMISTING KEROSENE CONFERENCE, FEBRUARY 18-19, 1981	JUNE 1981
ATR-81(6862)-1ND		THE AEROSPACE CORPORATION	ECONOMIC ASPECTS OF CONVERSION TO ANTIMISTING KEROSENE	NOVEMBER 1981
DOT/FAA/CT-82/12	P. G. WEITZ	SIMMONS PRECISION INSTRUMENT SYSTEMS DIVISION	COMMERCIAL AIRCRAFT AIRFRAME FUEL SYSTEMS SURVEY AND ANALYSIS	FEBRUARY 1982
NAEC-TR190		NAEC	LARGE-SCALE AIRCRAFT CRASH TESTS OF ANTIMISTING KEROSENE (FINAL REPORT)	5/21/82
DOT/FAA/CT-82/72	G. COFFINBERRY	GE	ANTIMISTING FUEL DEGRADER INVESTIGATION	JUNE 1982

REPORT NO.	AUTHOR	PERFORMING ORGANIZATION	TITLE	DATE
DOT/FAA/CT-82/95	E. KLUEG S. IMBROGNO B. FENTON	FAA TECH CENTER	AIRCRAFT FUEL SAFETY RESEARCH WITH ANTIMISTING FUELS - A STATUS REPORT	JUNE 1982
DOT/FAA/CT-82/19	R. FLEETER R. PETERSEN R. TOAZ A. JAKUB V. SAROHIA	JPL	ANTIMISTING KEROSENE ATOMIZATION AND FLAMMABILITY	JULY 1982
DOT/FAA/CT-82/80	P. G. WEITZ	SIMMONS PRECISION INSTRUMENT SYSTEMS DIVISION	COMMERCIAL AIRCRAFT AIRFRAME FUEL SYSTEMS SURVEY AND ANALYSIS	JULY 1982
DOT/FAA/CT-82/20	J. WAT V. SAROHIA	JPL	FRICTIONAL CHARACTERISTICS AND HEAT TRANSFER OF ANTIMISTING FUEL IN TUBES	AUGUST 1982
TS-129		TRANS SYTEMS CORPORATION	ANTIMISTING KEROSENE BENEFIT-COST SYSTEM SOFTWARE MODEL DESIGN	NOVEMBER 1982
DOT/FAA/CT-82/29	L. MHODD R. TALLEY	FALCON RESEARCH & DEVELOPMENT CO.	CORRELATION OF FLAMMABILITY TEST DATA ON ANTIMISTING FUELS	DECEMBER 1982
DOT/FAA/CT-82/93	R. MANNHEIMER	SMRI	DEGRADATION AND CHARACTERIZATION OF ANTIMISTING KEROSENE (AMK)	DECEMBER 1982
DOT/FAA/CT-82/18	A. YAVROUIAN M. SARBOLUKI V. SAROHIA	JPL	INFLUENCE OF LIQUID WATER AND WATER VAPOR ON ANTIMISTING KEROSENE (AMK)	FEBRUARY 1983
DOT/FAA/CT-82/116	F. CHUNG A. PEACOCK	DOUGLAS AIRCRAFT CO.	COMPATIBILITY STUDY OF ANTIMISTING KEROSENE AND THE DC-10/KC-10 FUEL SYSTEM	MARCH 1983
DOT/FAA/CT-82/59	B. AZAD P. POSTON	B&H TECHNOLOGICAL SERVICES, INC.	U.S. COMMERCIAL FLEET USAGE OF ANTIMISTING FUELS: SURVEY AND ANALYSIS	SEPTEMBER 1983
NAEC-TR198		NAEC	CRASH TEST OF AN F8-66 AIRCRAFT FUELED WITH ANTIMISTING KEROSENE FM-9	9/9/83
PWA 5697-65	A. FIORENTINO J. PLANELL	PRATT & WHITNEY AIRCRAFT GROUP	AN ASSESSMENT OF THE USE OF ANTIMISTING FUEL IN TURBOFAN ENGINES	OCTOBER 1983
DOT/FAA/CT-82/149	P. PARIKH R. FLEETER V. SAROHIA	JPL	ANTIMISTING FUEL BREAKUP AND FLAMMABILITY	DECEMBER 1983
DOT/FAA/CT-82/150	R. FLEETER P. PARIKH V. SAROHIA	JPL	ATOMIZATION AND COMBUSTION PERFORMANCE OF ANTIMISTING KEROSENE AND JET FUEL	DECEMBER 1983
DOT/FAA/CT-83/86	A. YAVROUIAN J. ERNEST V. SAROHIA	JPL	ANTIMISTING KEROSENE: BASE FUEL EFFECTS; BLENDING AND QUALITY CONTROL TECHNIQUES	JANUARY 1984
DOT/FAA/CT-TN 84/30	J. DERRICKSON	FAA TECH CENTER	PROCEDURE FOR ANALYZING ANTIMISTING KEROSENE USING GEL PERMEATION CHROMATOGRAPHY	AUGUST 1984
DOT/FAA/CT-84/15	P. MCCONNELL F. TOLLE H. MEHTA	BOEING MILITARY AIRPLANE CO.	AIRCRAFT WING FUEL TANK ENVIRONMENTAL SIMULATOR TESTS FOR EVALUATION OF ANTIMISTING FUELS	OCTOBER 1984
DOT/FAA/CT-TN 84/30	A. FERRARA W. CAVAGE	FAA TECH CENTER	FLAMMABILITY COMPARISON TEST APPARATUS OPERATOR'S MANUAL	MARCH 1985

REPORT NO.	AUTHOR	PERFORMANCE ORGANIZATION	TITLE	DATE
DOT/FAA/CT 85/1	R. HOOVER A. FERRARA	FAA TECH CENTER	PRACTICAL REAL-TIME QUALITY CONTROL OF ANTIMISTING KEROSENE	MAY 1985
DOT/FAA/CT 85/3		JPL	ANTIMISTING KEROSENE: EVALUATION OF FM VARIANTS	TO BE PUBLISHED
DOT/FAA/CT 85/4	A. YAVROUIAN P. PARIKH V. SAROHIA	FAA TECH CENTER	ANTIMISTING KEROSENE: EVALUATION OF FM-9 SD ADDITIVES	TO BE PUBLISHED
DOT/FAA/CT 85/5	R. MANNHEIMER	FAA TECH CENTER	REAL-TIME QUALITY CONTROL OF ANTIMISTING KEROSENE	TO BE PUBLISHED
DOT/FAA/CT 85/13	H. WEBSTER	FAA TECH CENTER	AMK FLAMMABILITY TESTS USING THE WING SPILLAGE FACILITY	TO BE PUBLISHED
DOT/FAA/CT T85/22	H.S. BRYNES E.P. KLUEG	FAA TECH CENTER	ANTIMISTING FUEL ADDITIVES STATUS REPORT	JULY 1985
DOT/FAA/CT 85/24	H.S. BRYNES	FAA TECH CENTER	DEVELOPMENT OF A LARGE-SCALE ANTIMISTING KEROSENE BLENDER	TO BE PUBLISHED
DOT/FAA/CT 85/24	P. PARIKH A. YAVROUIAN	FAA TECH CENTER	ANTIMISTING KEROSENE: DEVELOPMENT OF A CONTINUOUS 10 GPM INLINE BLENDER	TO BE PUBLISHED
DOT/FAA/CT 85/30	L.P. BERNAL V. SAROHIA	FAA TECH CENTER	EFFECT OF NON-NEWTONIAN ANTIMISTING KEROSENE ON JET PUMP PERFORMANCE	TO BE PUBLISHED
SAE AEROTECH 85	E.P. KLUEG	FAA TECH CENTER	ANTIMISTING FUEL TECHNOLOGY FOR TRANSPORT CATEGORY AIRCRAFT	OCTOBER 1985
16TH INT'L SEMINAR OF THE INT'L SOCIETY OF AIR SAFETY INVESTIGATORS	B.C. FENTON	FAA TECH CENTER	ANTIMISTING FUEL TECHNOLOGY APPLICATION IN FULL-SCALE TRANSPORT AIRCRAFT	SEPTEMBER 1985
DOT/FAA/CT 85/31	P. PARIKH A. YAVROUIAN R. PETERSON V. SAROHIA	FAA TECH CENTER	ANTIMISTING KEROSENE: EVALUATION OF LOW TEMPERATURE PERFORMANCE	TO BE PUBLISHED
DOT/FAA/CT 85/35	J.D. GREGORIE	FAA TECH CENTER	FULL-SCALE TRANSPORT CONTROLLED IMPACT DEMONSTRATION PROGRAM: JPL REPORT ON PHOTOGRAPHY/VIDEO COVERAGE PLAN	TO BE PUBLISHED
DOT/FAA/CT T85/62	E.P. KLUEG F.B. HOWARD	FAA TECH CENTER	EVALUATION OF EXPECTED EFFECTIVITY OF ANTIMISTING FUEL IN POST CRASH FIRE ACCIDENTS	TO BE PUBLISHED
DOT/FAA/CT T85/65	B.C. FENTON	FAA TECH CENTER	ANTIMISTING FUEL TECHNOLOGY APPLICATIONS IN FULL-SCALE TRANSPORT AIRCRAFT	TO BE PUBLISHED
DOT/FAA/CT T85/66	GENERAL ELECT. AIRCRAFT ENG. BUSINESS GROUP	FAA TECH CENTER	ANTIMISTING FUEL FLIGHT DEGRADER DEVELOPMENT AND AIRCRAFT FUEL SYSTEM INVESTIGATION VOLUMES I, II, III AND IV	TO BE PUBLISHED
		FAA TECH CENTER	FULL-SCALE TRANSPORT CID ACCIDENT INVESTIGATION	TO BE PUBLISHED

## ATTENDEE LIST

Mr. Nicholas G. Baz  
International Air Transport Association  
2000 Peel St.  
Montreal, Quebec, H3A 2R4 Canada

Mr. William Benjamin  
B&M Technologies Services, Inc.  
American Twine Office Park  
222 Third Street  
Cambridge, MA 02142

Mr. Merritt Birky  
National Transportation Safety Board  
800 Independence Avenue, S.W.  
Washington, D.C. 20594

Mr. Edmond Boullay  
MTA Embassy of France  
4101 Reservoir Rd N.W  
Washington DC 20007-2172

Mr. Stuart Bullock  
Rolls Royce, Ltd.  
P.O. Box 31  
Derby, England

Mr. Steve Casper  
United Airlines  
Maintenance Operations - SFOEG  
San Francisco Int'l Airport  
San Francisco, CA 94128

Mr. Arthur V. Churchill  
AFWAL/POSH  
Wright Patterson AFB  
Ohio 45433

Mr. Robert Clodfelter  
AFWAL/POSH  
Wright Patterson AFB  
Ohio 45433

Mr. William A. Curby  
Aviation Fuel Safety Co.  
7 Livery Road  
Chelmsford, MA 01824

Mr. James M. DeJovine  
ARCO Chemical Co.  
1500 Market St.  
Philadelphia, PA 19102

Mr. Robert Dodd  
Airline Pilots Association  
P.O. Box 1169  
Herndon, VA. 22070

Mr. John Doss  
Rolls Royce  
Atlanta, GA

Mr. Allan Driver  
British Aerospace  
P.O. Box 17414  
Dulles Airport, VA.

Mr. H. Richard Duffell  
Civil Aviation Authority  
Brabazon House  
Redhill, Surrey ENGLAND

Mr. William G. Dukek  
11 Ridge Road  
Summit, NJ 07901

Mr. Theodore E. Dumont  
Spectrum Association Inc.  
1101 Naugatuck Ave.  
Milford, Ct. 06460

Mr. Paul H. Erickson  
FAA  
ASO-250  
P.O. Box 20636  
Atlanta, GA 30344

Mr. William M. Fanning  
National Business Aircraft Association  
1200 18th Street, N.W.  
Washington, D.C. 20036

Mr. John Gallichan  
British Airways PLC  
Rm L333, TBA (S422)  
P.O. Box 10, Heathrow Airport (London)  
Hounslow, Middlesex  
TW62JA England

Mr. Greg Gandee  
U.S. Air Force  
AFISC/SES  
Norton AFB, CA 92409

Mr. Robert Glaser  
Walter Kidde  
2500 Airport Drive  
Wilson, N.C. 27893

Mr. Ron Grabois  
Conoco Speciality  
600 N. Dairy Ashford Road  
Houston, Texas 77052

Mr. Roy Harper  
ICI Corporate Colloid Science Group  
The Heath  
Runcorn  
Cheshire WA7 4QE  
ENGLAND

Warrant Officer Bob Henderson  
AIR/5511J1  
Naval Air Systems Command  
Washington, D.C. 20361-5510

Mr. David Hesterlee  
Delta Airlines, Inc.  
TOC-1 D559  
Atlanta Airport  
Atlanta, GA 30320

Mr. Frank B. Kelley  
Sikorsky Division of UTC  
Propulsion Engineering  
N. Main Street  
Stratford, Ct. 06602

Mr. Perry Kirklin  
Mobil R&D Group  
Billingsport Rd.  
Paulsboro, N.J. 08066

Peter Kochis  
Office of Aviation Safety  
ASF-300  
800 Indep. Ave SW  
Washington, D.C. 20591

Mr. David C. Lane  
Imperial Chemical Industries PLC  
Paints Division  
Wexham Road  
Slough, ENGLAND SL2 5D5

Mr. Jay Lowndes  
Engineering Editor  
Aviation Week & Space Tech Mag.  
1777 N. Kent Street  
Arlington, VA 22209

Mr. Ted Lyon  
General Electric Company  
Aircraft Engine Business Group  
1 Neumann Way M/D K-64  
Cincinnati, Ohio 45215

Mr. Richard Marshall  
Pratt & Whitney  
400 Main Street  
E. Hartford, Conn.

Mr. James McAbee  
ICI Americas, Inc.  
AMK Commercial Manager  
Fire Fighting Chemicals  
Wilmington, DE 19897

Dr. John V. McGovern  
311 North Street  
White Plains, N.Y. 10605

Mr. Peter Meiklem  
British Embassy  
3100 Massachusetts Ave., N.W.  
Washington, D.C. 20008

Mr. Nelson Miller  
FAA Technical Center ACT-301  
Atlantic City Airport, N.J. 08405

Mr. John Mossel  
ICI Americas, Inc.  
Specialty Chemicals Division  
Wilmington, DE 19897

Dr. Albert Moussa  
Arthur D. Little Inc.  
Cambridge, MA 02140

Mr. James Nicholson  
BP/ North American Petroleum  
Houston, Texas

Mr. Alexander R. Ogston  
Aviation Marine & Petroleum Consultant  
1 Park Street  
Tenafly, N.J. 07670

Mr. Eric J. Paisley  
FPT Inc.  
2580 Landmark Dr.  
Winston Salem, N.C. 27103

Mr. Roy E. Pardue  
Lockheed-Georgia Co.  
Dept. 72-66, Zone 311  
86 S. Cobb Dr.  
Marietta, GA 30063

Mr. Jack E. Pruitt  
Parker, Bertea Aerospace  
14113 Heritage Lane  
Silver Spring, MD 20906

Dr. Roy Reichenbach  
FAA APM-700  
800 Independence Ave., S.W.  
Washington, D.C. 20591

Mr. William Rix  
British Aerospace  
Civil Aircraft Division  
Hatfield, England AL109TL

Mr. Peter N. Roberts  
Transport CANADA  
Airworthiness Branch  
200 Kent Street  
M/S ABE/L  
Ottawa, Ontario K1A0N8

Ms. Jacqueline Rooths  
AIR-5511J3  
Naval Air Systems Command  
Wash. DC. 20361-5510

Mr. Robert Scott  
Airworthiness Branch  
Dept. of Aviation - Australia  
GPO Box 367  
Canberra, ACT, 2601 Australia

Admiral Owen W. Siler  
Aviation Fuel Safety Co.  
9809 Old Spring Rd.  
Kensington, Md. 20895

Mr. Maurice E. Shank  
Pratt & Whitney Engine Division  
400 Main Street M/S 162-31  
E. Hartford, Ct. 06108

Mr. Joseph Skinner  
Conoco Inc  
4637 RDW  
Ponca City, Okla 74603

Mr. Joseph D. Strachan  
Greenoak System  
97 Holbrooke Rd.  
White Plains, N.Y. 10605

Mr. Peter A. Stranges  
1420 16th St., N.W.  
Washington, D.C. 20006

Mr. Eugene Szetela  
United Technologies Research Center  
M/S 20  
East Hartford, CT 06108

Mr. A.F. Taylor  
Cranfield Institute of Technology  
Cranfield, Bedford  
MK430AL, England

Dr. W. F. Taylor  
Exxon Research & Engineering Co.  
Products Research Division  
P.O. Box 51  
Linden, NJ 07036

Mr. Brian Tufnell  
British Aerospace PLC  
Filton House  
Filton  
Bristol BS99 7AR  
England

Mr. Ed Versaw  
Lockheed California Co.  
P.O. Box 551 Dept. 75/44  
2555 North Hollywood Way  
Burbank, CA 91520

Mr. Fred Waite  
Imperial Chemical Industries PLC  
Wexham Road  
Slough, Berks, England SL2 5DS

Mr. Paul Washecheck  
Conoco, Inc.  
P.O. Box 1267  
Ponca City, OK 74601

Mr. Bob Wayman  
Box 727, Dep 0613  
Federal Express  
Memphis, Tenn. 38194-0613

Mr. Paul Weitz  
Simmond Precision Inst.  
Panton Road  
Vergennes, VT 05491

Mr. William Weitzer  
General Technology Applications  
12343-D Sunrise Valley Drive  
Reston, Va. 22091

Mr. John H. Wells  
Wallace Aircraft Division  
Cessna Aircraft Company  
P.O. Box 7704  
Wichita, KS 67277

Mr. Wilbur F. Wells  
FAA  
ASW-111  
P.O. Box 1689  
Fort Worth, Texas 76101

Mr. Gilbert Witlin  
Lockheed Aircraft Company  
Department 76-12, Bldg. 63, Plant A-1  
Burbank, CA 91520

Mr. Arthur M. Wittenberg  
Air Canada Base 15  
P.O. Box 9000  
Montreal International Airport  
Dorval, Quebec, Canada H4Y1C2

Mr. Edward C. Wood  
Flight Safety Foundation, Inc.  
5510 Columbia Pike  
Arlington, VA 22204

Mr. Mike Yaffee  
FAA Technical Center ACT-320  
Atlantic City Airport, N.J. 08405

Mr. A. Yavrouian  
NASA-JPL M/S 125-214  
4800 Oak Grove Drive  
Pasadena, CA 91109

## SPEAKER LIST

Mr. William W. Bannister  
Aviation Fuel Safety Company  
7 Livery Road  
Chelmsford, MA 01824

Mr. Steve Baxter  
Conoco, Inc.,  
Research and Development Department  
P.O. Box 1267  
Ponca City, Oklahoma 74601

Mr. Robert G. Bayless  
Capsulated Systems, Inc.  
P.O. Box 1351  
Fairborn, Ohio 45324

Mr. Neal A. Blake  
FAA Headquarters ADL-2A  
800 Independence Ave., S.W.  
Washington, D.C. 20591

Dr. Homer W. Carhart  
Naval Research Laboratory  
Code 6180  
Washington, D.C. 20375

Mr. John H. Enders  
Flight Safety Foundation, Inc.  
5510 Columbia Pike  
Arlington, VA 22204

Mr. Bruce Fenton  
FAA Technical Center ACT-320  
Atlantic City Airport, NJ 08405

Mr. Gene Klueg  
FAA Technical Center ACT-320  
Atlantic City Airport, NJ 08405

Mr. A.D. Krisch  
Professor of Physics  
The University of Michigan  
Ann Arbor, Michigan 48109-1120

Dr. R. Mannheimer  
Southwest Research Institute  
8500 Culebra Road  
San Antonio, Texas 78284

The Honorable Norman Y. Mineta  
Chairman, Subcommittee on Aviation  
Committee on Public Works and Transportation  
House of Representatives  
Washington, D.C. 20515

Mr. Lawrence Neri  
FAA Technical Center ACT-330  
Atlantic City Airport, N.J. 08405

Dr. P. Parikh  
NASA-JPL M/S 125-214  
4800 Oak Grove Drive  
Pasadena, CA 91109

Mr. Tom Peacock  
M/C 36-41  
Douglas Aircraft Company  
3855 Lakewood Boulevard  
Long Beach, California 90846

Mr. Charles Rivers  
ICI Americas, Inc.  
Wilmington, Delaware 19897

Dr. V. Sarohia  
NASA-JPL M/S 125-214  
4800 Oak Grove Drive  
Pasadena, CA 91109

Mr. F.W. Schaeckel  
Chief, Fuels & Lubricants Branch  
U.S. Army  
Belvoir Research & Development Center  
Ft. Belvoir, Virginia 22060-5606

Mr. Donald A. Schroeder  
FAA Headquarters APM-710  
800 Independence Ave., S.W.  
Washington, D.C. 20591

Professor Dale L. Schruben  
Department of Chemical Engineering  
University of Akron  
Akron, Ohio 44325

Mr. Bruce Singer  
FAA Technical Center ACT-300  
Atlantic City Airport, NJ 08405

Mr. Howard Skavdahl  
Boeing Commercial Airplane Company  
P.O. Box 3703 M/S 9W-60  
Seattle, WA 98124

Dr. Martin Summerfield  
Princeton Combustion Research Labs  
475 U.S. Highway One  
Monmouth Junction, New Jersey 08540

Mr. Horace Allen Tansill  
Consultant  
P.O. Box 480  
Santa Barbara, CA 93102

Mr. Dick Tobiason  
Air Transport Association of America  
1709 New York Avenue, N.W.  
Washington, D.C. 20006

Mr. Jerry Trippe  
General Technology Applications, Inc.  
12343D Sunrise Valley Drive  
Reston, Virginia 22091

Mr. William Westfield  
FAA Technical Center ACT-320  
Atlantic City Airport, NJ 08405

Mr. S.P. Wilford  
RAE, Farnborough, Hants  
GU146TD England

Mr. Alan E. Zengel  
Coordinating Research Council, Inc.  
219 Perimeter Center Parkway  
Atlanta, Georgia 30346

END

DTIC

8-86